ENGINE PERFORMANCE AND EXHAUST EMISSIONS OF A DIESEL ENGINE
FROM VARIOUS BIODIESEL FEEDSTOCK

A Thesis

by

BJORN SANCHEZ SANTOS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Biological and Agricultural Engineering
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Approved by:
Chair of Committee, Sergio C. Capareda
Committee Members, Ronald E. Lacey
Timothy J. Jacobs
Head of Department, Gerald L. Riskowski

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ABSTRACT

Engine Performance and Exhaust Emissions of a Diesel Engine from Various Biodiesel Feedstock. (December 2009)

Bjorn Sanchez Santos, B.S., University of the Philippines at Los Baños

Chair of Advisory Committee: Dr. Sergio C. Capareda

Increasing fuel prices, stricter government policies, and technological developments made it possible to seek for renewable alternatives, called biofuels, to petroleum fuel. Biodiesel, a biofuel that is produced from chemically mixing animal fat, vegetable oils, or recycled restaurant grease with alcohol and catalyst, is gaining popularity in recent years as a substitute for petroleum diesel. Ninety percent (90%) of U.S. biodiesel industry makes use of soybean oil as its feedstock. However, soybean oil alone cannot meet such a huge demand on biofuel production. Hence, it is important to identify and get more information about other feedstocks, specifically on its effects on the performance and exhaust emissions of diesel engines.

The purpose of this study is to investigate the performance and emissions of two diesel engines operating on different biodiesel fuels (i.e. canola oil, sunflower oil, safflower oil, peanut oil, and chicken fat) and compare them to the performance and emissions when the engine is operated on soybean oil-based biodiesel and petroleum-based diesel.
Results indicated that an engine operating on biodiesel generates a little less power and torque at any given speed than one running on diesel. Such power and torque loss were attributed to the biodiesel’s lower energy content. The lower heating value (energy content) of biodiesel can be reflected in the specific fuel consumption, i.e., to generate the same power, more biodiesel is needed. The reduction in torque and power of less than 10% indicates that in some cases biodiesel has better combustion than diesel. Unfortunately, the high efficiency of combustion may give rise to increased combustion temperature which may lead to higher exhaust emissions.

The gradual decrease in the total hydrocarbon and CO$_2$ emissions, as blends were increased from B20 to B100, was also found to be an indication of better combustion using biodiesel fuels than petroleum diesel. However, NOx emissions were higher, predominantly at low speeds for most biodiesel and blends and therefore may require some additives or engine modifications/or adjustments to equalize the NOx emissions of diesel. Other emissions particularly SO$_2$ were lower than standards require.
DEDICATION

To my Mommy Gregoria, Daddy Primo, and good friends, Jep, and Tata…
ACKNOWLEDGEMENTS

I would like to thank my professor, Dr. Sergio Capareda, for having patience with me and for giving inspiration for the creation of this work. I would also like to thank the members serving on my thesis committee. Thanks to Dr. Ronald Lacey and Dr. Tim Jacobs for their valuable feedback and suggestions. Thanks to the Houston Advanced Research Center for funding this research. Also, I would like to thank the Texas A&M University Department of Biological and Agricultural Engineering for offering me the amazing opportunity to study at Texas A&M.

I would be remiss without thanking my fellow graduate students and all of the student workers who helped me complete this research. There is no possible way that I could have done any part of this study without their constant support and encouragement. To Amado Maglinao Jr., Joan Hernandez, Froilan Aquino, Nathan Ball, Ordway Boriack, Jared Murdock, Nicole Pennington, Brian Edmondson, and Stephanie Rosario, words are not enough to express my sincere appreciation for all of your help.

Thanks to my family who have been there for me every step of the way. Thanks to all my Titos, Titas, and cousins in California especially Reggie, Samantha, Kuya Jason, Joshua, and Ryan for spending time with me especially during those brief vacation trips. Thanks to my family in the Philippines for their undying support through simple yet limitless text messages and Skype calls. Thanks to Hapi, my brother Hanchi, my sister Minette, my cousins Jeff and Beng, my Tita Nene, Topher, and my parents Bong and Monette. I would not survive graduate studies without ya’ll. I could not have
physically or mentally made it through this without each of you. I am a smarter student, a stronger worker, and a better person because of all of you. Thank you from the bottom of my heart.

Last, but certainly not least, words cannot express my gratitude to God for giving me the gifts that got me here in the first place.
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSFC</td>
<td>Brake-specific fuel consumption, g/kW-h</td>
</tr>
<tr>
<td>CFME</td>
<td>Chicken fat biodiesel/ chicken fat methyl ester</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>PME</td>
<td>Peanut oil biodiesel/ peanut oil methyl ester</td>
</tr>
<tr>
<td>REF-DIESEL</td>
<td>Standard no. 2 ultra-low sulfur diesel</td>
</tr>
<tr>
<td>RME</td>
<td>Canola oil biodiesel/ canola oil methyl ester</td>
</tr>
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<td>SaFFME</td>
<td>Safflower oil biodiesel/ safflower oil methyl ester</td>
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<tr>
<td>SFME</td>
<td>Sunflower oil biodiesel/ sunflower oil methyl ester</td>
</tr>
<tr>
<td>SME</td>
<td>Soybean oil biodiesel/ soybean oil methyl ester</td>
</tr>
<tr>
<td>ULSD</td>
<td>Ultra-low sulfur diesel</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Objectives</td>
<td>7</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>8</td>
</tr>
<tr>
<td>2.1 Background on Biodiesel</td>
<td>8</td>
</tr>
<tr>
<td>2.1.1 Biodiesel vs. Petroleum Diesel</td>
<td>9</td>
</tr>
<tr>
<td>2.1.2 Biodiesel Feedstock</td>
<td>10</td>
</tr>
<tr>
<td>2.1.3 Biodiesel Standards</td>
<td>13</td>
</tr>
<tr>
<td>2.2 Engine Performance</td>
<td>14</td>
</tr>
<tr>
<td>2.2.1 Net Brake Power and Torque</td>
<td>14</td>
</tr>
<tr>
<td>2.2.2 Brake-specific Fuel Consumption</td>
<td>16</td>
</tr>
<tr>
<td>2.3 Exhaust Emissions</td>
<td>18</td>
</tr>
<tr>
<td>3. METHODOLOGY</td>
<td>20</td>
</tr>
<tr>
<td>3.1 Preparation of Vegetable Oils</td>
<td>21</td>
</tr>
<tr>
<td>3.1.1 Extraction of Oils</td>
<td>21</td>
</tr>
<tr>
<td>3.1.2 Vegetable Oil Refining</td>
<td>23</td>
</tr>
<tr>
<td>3.1.2.1 Degumming and Neutralization</td>
<td>23</td>
</tr>
<tr>
<td>3.1.2.2 Dewaxing and Bleaching</td>
<td>23</td>
</tr>
<tr>
<td>3.2 ASTM Characterization of Biodiesel Fuels</td>
<td>24</td>
</tr>
<tr>
<td>3.2.1 Test Fuels</td>
<td>24</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.3 Engine Performance and Exhaust Emissions Testing</td>
<td>25</td>
</tr>
<tr>
<td>3.3.1. Test Equipment</td>
<td>25</td>
</tr>
<tr>
<td>3.3.2. Instrumentation and Data Acquisition Equipment</td>
<td>27</td>
</tr>
<tr>
<td>3.3.3. Experimental Method</td>
<td>30</td>
</tr>
<tr>
<td>4. RESULTS, ANALYSES AND DISCUSSIONS</td>
<td>34</td>
</tr>
<tr>
<td>4.1 Oil Extraction</td>
<td>34</td>
</tr>
<tr>
<td>4.2 Vegetable Oil Refining</td>
<td>36</td>
</tr>
<tr>
<td>4.3 ASTM Characterization of Biodiesel Fuels</td>
<td>38</td>
</tr>
<tr>
<td>4.4 Engine Performance</td>
<td>39</td>
</tr>
<tr>
<td>4.4.1. Small Engine</td>
<td>39</td>
</tr>
<tr>
<td>4.4.1.1. Comparison between Fuel Blends</td>
<td>40</td>
</tr>
<tr>
<td>4.4.1.2. Comparison between Biodiesel Feedstock</td>
<td>47</td>
</tr>
<tr>
<td>4.4.2. Large Engine</td>
<td>50</td>
</tr>
<tr>
<td>4.4.2.1. Comparison between Fuel Blends</td>
<td>51</td>
</tr>
<tr>
<td>4.4.2.2. Comparison between Biodiesel Feedstock</td>
<td>57</td>
</tr>
<tr>
<td>4.4.3. Summary</td>
<td>62</td>
</tr>
<tr>
<td>4.5 Exhaust Emissions</td>
<td>64</td>
</tr>
<tr>
<td>4.5.1. Small Engine</td>
<td>64</td>
</tr>
<tr>
<td>4.5.1.1. Comparison between Fuel Blends</td>
<td>64</td>
</tr>
<tr>
<td>4.5.1.2. Comparison between Biodiesel Feedstock</td>
<td>68</td>
</tr>
<tr>
<td>4.5.2. Large Engine</td>
<td>69</td>
</tr>
<tr>
<td>4.5.2.1. Comparison between Fuel Blends</td>
<td>69</td>
</tr>
<tr>
<td>4.5.2.2. Comparison between Biodiesel Feedstock</td>
<td>76</td>
</tr>
<tr>
<td>4.5.3. Summary</td>
<td>80</td>
</tr>
<tr>
<td>5. SUMMARY AND CONCLUSIONS</td>
<td>82</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>85</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>89</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>95</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>109</td>
</tr>
<tr>
<td>APPENDIX D</td>
<td>110</td>
</tr>
<tr>
<td>APPENDIX E</td>
<td>122</td>
</tr>
<tr>
<td>VITA</td>
<td>147</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U.S. energy consumption in 2007</td>
</tr>
<tr>
<td>2</td>
<td>Projected biofuels demand (million barrels/day) from 1970 to 2030</td>
</tr>
<tr>
<td>3</td>
<td>Overview of the processes involved in the study</td>
</tr>
<tr>
<td>4</td>
<td>The dynamometer test system showing (A) 14.2 kW diesel engine, and (B) the dynamometer</td>
</tr>
<tr>
<td>5</td>
<td>JD 4045DF150 diesel engine used for performance and emissions testing</td>
</tr>
<tr>
<td>6</td>
<td>Schematics of the data acquisition system for the Yanmar 3009D and JD 4045DF150 diesel engines</td>
</tr>
<tr>
<td>7</td>
<td>Relationship between percent oil extracted and extruder sizes of the three oil seeds (peanut, sunflower, and safflower)</td>
</tr>
<tr>
<td>8</td>
<td>Relationship between temperature (°C), % oil extraction and duration of extraction (min) using extruder # 5 (5.33mm dia) on shelled peanuts</td>
</tr>
<tr>
<td>9</td>
<td>Breakdown of the percent composition of (a) safflower oil, (b) peanut oil, and (c) sunflower oil, all showing the by-products of the vegetable oil refining processes</td>
</tr>
<tr>
<td>10</td>
<td>Relationship between engine performance parameters and percentage of soybean oil biodiesel in a fuel blend</td>
</tr>
<tr>
<td>11</td>
<td>Relationship between engine performance parameters and percentage of canola oil biodiesel in a fuel blend</td>
</tr>
<tr>
<td>12</td>
<td>Relationship between engine performance parameters and percentage of peanut oil biodiesel in a fuel blend</td>
</tr>
<tr>
<td>13</td>
<td>Relationship between engine performance parameters and percentage of sunflower oil biodiesel in a fuel blend</td>
</tr>
</tbody>
</table>
Figure 14  Net brake power (kW) versus engine speed of the 14.2 kW Yanmar 3009D diesel engine using ultra-low sulfur diesel and test biodiesel fuels .......................................................... 48

Figure 15  Relationship between brake-specific fuel consumption (g/kW-h) and engine speed using test fuels B100 SME, B100 RME, B100 PME, and B100 SFME, and reference fuel REFDIESEL. Data were taken from the Yanmar engine described earlier .......... 49

Figure 16  Relationship between engine performance parameters and percentage of soybean oil biodiesel in a fuel blend. Data were taken from JD 4045DF150 engine .............................................................. 52

Figure 17  The effects of the RME fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption ......................................................... 54

Figure 18  The effects of the peanut oil biodiesel fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption ......................................................... 55

Figure 19  The effects of chicken fat biodiesel fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption ......................................................... 58

Figure 20  Net brake power (kW) versus engine speed of JD 4045DF150 diesel engine using REFDIESEL and test biodiesel fuels.............. 59

Figure 21  Torque produced (N-m) versus engine speed (rpm) of JD 4045DF150 diesel engine using REFDIESEL and test biodiesel fuels............ 59

Figure 22  Plot of the brake specific fuel consumption (g/kW-h) against engine speed (rpm). Data taken from JD 4045DF150 diesel engine tests .... 60

Figure 23  Effects of peanut oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the Yanmar diesel engines ........ 66

Figure 24  Effects of sunflower oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the Yanmar diesel engine........... 67

Figure 25  Oxides of nitrogen (NOx) concentrations of Yanmar 3009D diesel engine using ULSD (standard no. 2) fuel and biodiesel test fuels .... 68
Figure 26  Carbon dioxide (CO2), carbon monoxide (CO), total hydrocarbon (THC) and sulfur dioxide (SO2) concentrations of Yanmar 3009D diesel engine using ULSD (standard no. 2) and biodiesel test fuels

Figure 27  Effects of soybean oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine

Figure 28  Effects of canola oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine

Figure 29  Effects of peanut oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine

Figure 30  Effects of chicken fat biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine

Figure 31  Oxides of nitrogen (NOx) concentrations of JD 4045DF150 diesel engine using ULSD standard no. 2 diesel and test biodiesel fuels

Figure 32  Carbon dioxide (CO2), carbon monoxide (CO), total hydrocarbon (THC) and sulfur dioxide (SO2) concentrations of JD 4045DF150 diesel engine using ultra-low sulfur (standard no. 2) farm diesel and test biodiesel fuels
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Summary of biodiesel testing standard ASTM D 6751</td>
<td>13</td>
</tr>
<tr>
<td>Table 2</td>
<td>General specifications for Yanmar 3009D and JD 4045DF150 diesel engines used</td>
<td>26</td>
</tr>
<tr>
<td>Table 3</td>
<td>Test fuel characteristics as indicated by ASTM 6751 standard</td>
<td>38</td>
</tr>
<tr>
<td>Table 4</td>
<td>Analysis of variance for the BSFC at peak torque conditions of the four test fuels</td>
<td>49</td>
</tr>
<tr>
<td>Table 5</td>
<td>Results of the Fisher’s LSD statistical method on the BSFC of the four test fuels and reference diesel fuel</td>
<td>50</td>
</tr>
<tr>
<td>Table 6</td>
<td>Analysis of variance for the BSFC of JD 4045DF150 using six types of biodiesel fuels</td>
<td>61</td>
</tr>
<tr>
<td>Table 7</td>
<td>Results of the Fisher’s LSD statistical method on the BSFC of the four test fuels and reference diesel fuel</td>
<td>61</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

Diesel engines were developed, originally, to run using vegetable oils. In 1900, the French Otto company has demonstrated a diesel engine using peanut oil as fuel at the World Fair in Paris, France (Knothe, 2001). This became an inspiration to the German Engineer, Rudolf Diesel, where he believed that the utilization of biomass fuel was the real future of his engine. However at that time, due to the abundant supply of petroleum-based diesel fuel and earlier problems faced by engineers in running vegetable oils, engine manufacturers altered their engines to utilize the lower viscosity of petroleum diesel rather than the vegetable oil.

For many years, petroleum diesel has been the fuel of choice for diesel engines. However, increasing fuel prices, stricter government policies, and technological developments have made researchers and engineers to re-evaluate vegetable oils for use as fuel for modern diesel engines. Surpluses of basic food commodities in the past few decades have also encouraged interest in developing new uses for agricultural materials. Technological advances in growing and cultivating crops increased the amount of crops harvested per unit of land and lowered the cost of feedstock for crop production (Shapouri and Duffield, 1993).

Moreover, the heightened competition from other countries is making it tougher for the U.S. grains and crops (e.g. soybeans, corn, etc.) to compete in global markets. Hence, farmers are finding other ways to utilize these agricultural produce.

This thesis follows the style of Transactions of the ASAE.
Policy makers and consumers, on the other hand, are demanding products that can reduce the country’s dependence on petroleum imports and pushing to find substitutes for products that are harmful to the environment.

Biodiesel, which is produced from chemically mixing animal fat, vegetable oils, or recycled restaurant grease with an alcohol and catalyst, is gaining popularity in recent years as a substitute to petroleum diesel since it is nontoxic, biodegradable, and essentially free of sulfur and aromatics. According to the National Biodiesel Board (2008a), it works in any diesel engine with few or no modifications and offers a modest amount of impact to an engine’s operating performance. Blends of 20 percent by volume biodiesel with 80 percent by volume petroleum diesel (B20) can generally be used in unmodified diesel engines. Some manufacturers warrant the use of biodiesel blends up to B20 in diesel engines. In December 2007, the Texas Commission on Environmental Quality (TCEQ) approved biodiesel blends comprised of 5 percent or less by volume biodiesel (B5) and 95 percent or more by volume diesel fuel (TCEQ, 2007). Biodiesel blends above B5 and up to B20 are also legal fuel in Texas, provided they are added with TCEQ approved additives.

According to Shapouri and Duffield (1993), it may take some time for the biodiesel fuel to economically compete with and substitute diesel fuels. Nonetheless, biodiesel may be used as one of the additives to improve lubricity of ultra-low sulfur diesel (ULSD) fuel, which is negatively affected by the removal of sulfur to meet the ULSD standards. Sulfur in diesel fuel acts as an engine lubricant. This is important because reducing sulfur content may lead to a reduction of fuel lubricity. While newer
engines may be designed to handle low sulfur fuel, older engines may not. Fueling an older model engine with low sulfur diesel for an extended period of time may result in injector plugging (Powell, 2007).

According to the 2007 report of the Energy Information Administration (EIA, 2009a) on the renewable energy trends in consumption and electricity, the U.S. energy consumption is highly dependent on petroleum and coal, with only 7% of the total consumption utilizes renewable energy (Figure 1). Biomass energy consumption stood at 3,596 trillion Btu or 53 percent of the renewable energy market in 2007.

![Figure 1. U.S. Energy consumption in 2007. (EIA, 2009a)](image)

Recent increases in oil prices and demand for less foreign energy dependency have led to a push for producing alternative fuels. According to Pradhan et al. (2008), biodiesel production in the U.S. has grown rapidly. It has increased from under 1.89
million liters (1/2 million gallons) in 1999 to over 568 million liters (150 million gallons) in 2006. The Energy Information Administration (EIA, 2009b) projects U.S. demand for biofuels will increase from 0.48 million barrels per day (MMbd) in 2007 to 2.39 million barrels per day (MMbd) in 2030 (Figure 2). Despite the recent economic downturn, growing demand for energy and efforts by petroleum-producing countries to limit access to their oil reserves, in the long run, are expected to lead to an increase in petroleum oil prices. With this trend, more alternative fuels such as biodiesel are expected to be produced and U.S. dependence on foreign petroleum may decline in the following years.

Figure 2. Projected Biofuels demand (million barrels/day) from 1970 to 2030. (EIA, 2009b)
Most of the biodiesel fuels being produced in the U.S. are made from soybean oil. In 2007, soybeans represented 56 percent of the world oilseed production, in which 32 percent of those soybeans were produced in the United States. Soybeans were planted on 63.6 million acres (25.7 million hectares); producing 2.585 billion bushels (70.36 million metric tons). According to the National Biodiesel Board (2008b), each bushel of soybean being produced can be converted into 1.5 gallons of biodiesel and 48 pounds of protein-rich meal. If all of the soybeans being produced are converted into biodiesel, the United States can produce 10.623 million gallons/day or 0.253 MMbd of biodiesel. This could have lessened the gap between the supply and demand on biofuels in 2007. However, soybeans are being utilized for other means as well. Such that 49% of the U.S. total soybean oil consumption is utilized for salads and cooking oil; 27% are for baking and frying fats; while only 18% are being used for industrial products (i.e. biodiesel included).

Other feedstock may have to be discovered or developed in order to close such a gap. Therefore, it necessary to investigate on other feedstock produced in the United States such as safflower, sunflower, canola and peanut oil.

Stricter government policies such as the ULSD standards and Clean Air Act of 1990 had also made a drive for researchers to develop new and better alternative fuels to petroleum diesel. The Environmental Protection Agency (EPA) has reported in 2004 that non-road diesel engines have a substantial role in contributing to the nation’s air pollution. These non-road diesel engines are primarily used in construction, agricultural, and industrial applications and may have been projected to continue to contribute large
amounts of particulate matter, nitrogen oxides, and sulfur oxides, all of which contribute to serious public health problems in the United States.

Effective August 30, 2004, the EPA has adopted new emissions standards for non-road diesel engines and sulfur reductions in non-road diesel fuel. These changes should reduce harmful emissions, as well as help states and local areas designated as 8-hour ozone non-attainment areas to improve their air quality. A two-step sulfur standard for non-road, locomotive, and marine (NRLM) diesel fuels has been finalized by the EPA. According to the standard, beginning June 1, 2007, refiners will be required to produce NRLM diesel fuel with a maximum sulfur content of 500 ppm. Then, beginning June 1, 2010, the sulfur content will be reduced for non-road diesel fuel to 15 ppm (EPA, 2004). This standard will achieve considerable, cost-effective reductions of sulfate PM and SO$_2$ emissions, which will provide substantial public health and environmental benefits, which outweigh the cost of meeting the standards necessary to achieve them. The final sulfur standards will also allow high efficiency control technology to be applied to non-road engines, since sulfur can inhibit or impair the function of diesel exhaust emission control devices that will be necessary for non-road diesel engines to meet the finalized emission standards (EPA, 2004).

With all these factors (i.e. increasing fuel prices, stricter government policies, and technological advancements) in hand, many researchers have re-evaluated vegetable oils as a substitute fuel for petroleum diesel. It is important to understand and gain more information on feedstock potential for biodiesel production, such as sunflower,
safflower, canola and peanut oil, particularly on its fuel characteristics and effects on the operating performance and exhaust emissions of non-road diesel engines.

1.1 Objectives

The purpose of this research is to investigate the performance and exhaust emissions of two types of diesel engines operating on biodiesel fuels derived from various sources (i.e. canola oil, sunflower oil, safflower oil, peanut oil, and chicken fat) and compare them to the performance and exhaust emissions when the engine is operated on soybean oil-based biodiesel and petroleum-based diesel. The specific objectives of the study are as follows:

(a) To gain more information on the oil extraction, refining, and biodiesel fuel characteristics of sunflower, safflower, and peanut oil;
(b) To perform ASTM characterization and assess biodiesel quality of the test fuels;
(c) To determine the relationship between the characteristic engine performance (i.e. brake horsepower, torque and specific consumption) and the percentage of biodiesel in fuel blends;
(d) To determine the relationship between pollutant concentrations (i.e. NOx, SO2, THC, CO and CO2) in a diesel engine exhaust and the percentage of biodiesel in fuel blends; and
(e) To evaluate the differences in performances and exhaust emissions between different biodiesel feedstock under study (i.e. soybean oil, canola oil, sunflower oil, safflower oil, peanut oil, and chicken fat).
2. LITERATURE REVIEW

In order to evaluate biodiesel effects on engine performance and emissions, one has to understand the science that encompasses it. Biodiesel, in itself, is already a complex entity in which every biodiesel feedstock has its own characteristics that can evidently influence the production cost, engine performance, and exhaust emissions. Hence, the next few sections are devoted to provide a background and related studies associated with biodiesel characteristics (i.e. feedstock, fuel properties, standards, regulations, etc.), engine performance, and exhaust emissions.

2.1 Background on Biodiesel

Biodiesel is defined as mono-alkyl esters of long chain fatty acids made through a chemical process called transesterification whereby the glycerin is separated from the animal fat or vegetable oil. The process leaves behind two products - methyl esters (biodiesel) and glycerin, which is a valuable byproduct usually sold to be used in soaps and other cosmetic products.

There are three basic routes to ester production from oils and fats. These are: (1) Base catalyzed transesterification of the oil with alcohol; (2) Direct acid catalyzed esterification of the oil with methanol; and (3) Conversion of the oil to fatty acids, and then to alkyl esters with acid catalysis. However, majority of the alkyl esters produced today are done with base catalyzed reaction due to its high conversion rates (98%) with
minimal side reactions and reaction time. Conversion to methyl esters using base catalyzed reaction also makes the process straightforward with no intermediate steps.

2.1.1. Biodiesel vs. Petroleum Diesel

When comparing various petroleum fuel alternatives, the single most important factor would be that the alternative has to be a significantly better option to these fossil-based fuels. Although petroleum diesel has been in use for many years, it may no longer be an efficient resource due to its negative impacts on the environment.

Biodiesel has already proven itself to be a viable resource (EPA, 2002; NBB, 2008b). Unlike regular diesel which is derived from petroleum, biodiesel comes from natural resources such as animal fat or various vegetable oils. Biodiesel can be used in an engine that runs on regular diesel. Biodiesel is free of sulfur, such that it does not contain the typical aerosols derived from sulfuric acid that forms in the exhaust system when diesel fuel is used (Munoz et al., 2004). Moreover, biodiesel appears to reduce particulate emissions and volatile organic compounds without significantly reducing horsepower, gas mileage or engine durability. (Shapouri and Duffield, 1993)

In addition to these ecological benefits, the CO₂ balance of biodiesel is positive. Biodiesel is a bio-based fuel that will provide yet another market for agricultural commodities. It is because of these advantages that biodiesel is again being evaluated for use as a fuel for modern diesel engines (Schumacher et al., 2001).

However, the use of biodiesel has its drawbacks. According to Quinn (2009), problems associated with biodiesel results from the presence of moisture in the fuel. A
problem associated with moisture in the fuel is that it reduces the power given to the engine and causes it to have a harder starting up time. Water also causes serious corrosion in certain components like water pumps and fuel lines. If the water freezes inside the fuel lines then that could pose a significant problem as well. Additionally, having a heated tank does not help much either since it may cause microbial production.

Despite these drawbacks, there is still a strong demand for biodiesel fuels to be used in diesel engines. Such factors like stricter government policies, advancements in agriculture, and increasing petroleum diesel prices could make biodiesel production continue to grow in the years to come (EIA, 2009a).

2.1.2. Biodiesel Feedstock

There are numerous studies on soybean oil as a biodiesel feedstock due to its availability in the market (Altin et al., 2000; Canakci and Van Gerpen, 2003; Dorado et al., 2002; Grabowski and McCormick, 1998; Hansen et al., 2006; McDonald et al., 1995; Pradhan et al., 2008; Schumacher et al., 1992; Schumacher et al., 2001). However, as described earlier, soybean oil alone cannot handle the demand on biofuel production, hence, other feedstock may have to be discovered and identified.

A variety of oils and fats can be used to produce biodiesel. While soybean is the most common biodiesel feedstock in the U.S., rapeseed oil on the other hand, is the preferred oil stock for biodiesel production in most of Europe. This is partly because of the high level of development of rapeseed production in Europe. Rapeseed is said to produce more oil per unit of land area compared to other oil sources. There is however a
concern over the use of rapeseed as biodiesel since it emits nitrous oxide (N\textsubscript{2}O), which is a potent greenhouse gas and air pollutant, during its crop production stages. Considered over a 100 year period, N\textsubscript{2}O has 296 times higher global warming potential than CO\textsubscript{2}. It has been estimated that 3\% to 5\% of the nitrogen fertilizer used to grow rapeseed is converted to N\textsubscript{2}O (Lewis, 2007).

Other feedstocks, such as safflower, peanut and sunflower oils, and animal fats are recently being studied as potential feedstocks for biodiesel production. Safflower oil is used mainly as cooking oil, in salad dressing, and for the production of margarine. In a study conducted by Meka et al. (2007) on the synthesis of biodiesel from safflower oils, they indicated that safflower oil contains 75-80\% linoleic acid such that the presence of this unsaturated acid is useful in improving low temperature fuel properties like pour point, cloud point, and cold filter plugging point. In their study, they investigated the effects of temperature, molar ratio (oil to alcohol), and concentration of catalyst on synthesis of biodiesel fuel using safflower oil. Results indicated that the better suitable conditions for biodiesel synthesis are of 1:6 molar ratio (oil to alcohol), 60\textdegree C temperature, and catalyst concentration of 2\% (by wt. of oil).

Peanut oil is also a suitable feedstock for biodiesel production, but there is very little published information regarding peanut oil biodiesel. Recently, there are studies being conducted in the University of Georgia wherein researchers are trying to develop non-edible peanuts that are high in oil, and could be grown specifically for biodiesel production. These new strains are higher in oil content than currently grown varieties and would not compete with peanuts grown for food and commercial cooking oil.
products. According to Roberson (2006), food-grade peanut oil produces approximately 123 gallons of biodiesel per acre, compared to 50 gallons for soybean oil. The problem with peanut oil is that it is much more valuable in the world market for food use, hence, making its conversion into biodiesel more economically impractical.

Similar to peanut oil biodiesel, research on sunflower oils made into esters were very limited (Kaufman and Ziejewski, 1984; Moreno et al., 1999; Munoz et al., 2004). The U.S. ranked 6th in the world in producing sunflower seeds; exporting to countries such as Russia, Mexico and most of Europe. According to the 2008 USDA data on crop production, the U.S. sunflower production totaled 3.42 billion pounds, which is up more than 19% from 2007 and up by nearly 60% from the 2006 crop size. Production of oil-type sunflower seeds, at 2.99 billion pounds, was up nearly 21% from 2007’s 2.48 billion pounds. Yields averaged 1,452 pounds, about on par with 2007 levels. These improvements in crop production makes sunflower oil a viable contender for biodiesel production.

Some researchers have also turned to chicken fat as it is a less-expensive substitute for soybean oil. However, raw chicken fat have high presence of free fatty acids. Fatty acids create problems in the transesterification process because they tend to form soaps as a by-product. These soaps increase the formation of gels, which make it more difficult to produce high yield and good quality biodiesel fuels out of chicken fat. Moreover, information regarding this type of feedstock is rather limited at this time.
2.1.3. Biodiesel Standards

In order to ensure proper performance of a diesel engine, biodiesel has to meet strict industry specifications. The ASTM 6751, developed by the American Society for Testing and Materials (ASTM) International, specifies various test methods to be used in the determination of certain properties for biodiesel blends. For biodiesel producers to sell their biodiesel commercially, they must meet such standards. A summary table of the standard is shown in Table 1. Some of the tests mentioned include flash point, kinematic viscosity, cetane number, cloud point, oxidation stability, and acid number.

Table 1. Summary of biodiesel testing standard ASTM D 6751. (ASTM, 2008)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method¹</th>
<th>Grade 915 Limits</th>
<th>Grade 9500 Limits</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium and Magnesium, combined</td>
<td>EN 14536</td>
<td>5 max</td>
<td>5 max</td>
<td>ppm (µg/g)</td>
</tr>
<tr>
<td>Flash point (closed cup)</td>
<td>D 93</td>
<td>93 min</td>
<td>93 min</td>
<td>ºC</td>
</tr>
<tr>
<td>Alcohol content</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water and sediment</td>
<td>D 2709</td>
<td>0.050 min</td>
<td>0.050 min</td>
<td>% volume</td>
</tr>
<tr>
<td>Kinematic viscosity, 40°C</td>
<td>D 445</td>
<td>1.9 - 6.6 (g)</td>
<td>1.9 - 6.6 (g)</td>
<td>mm²/s</td>
</tr>
<tr>
<td>Sulfated ash</td>
<td>D 874</td>
<td>0.020 max</td>
<td>0.020 max</td>
<td>% mass</td>
</tr>
<tr>
<td>sulfur (g)</td>
<td>D 5433</td>
<td>0.0015 max (15)</td>
<td>0.05 max (500)</td>
<td>% mass (ppm)</td>
</tr>
<tr>
<td>Copper strip corrosion</td>
<td>D 139</td>
<td>No. 3 max</td>
<td>No. 5 max</td>
<td></td>
</tr>
<tr>
<td>Cetane number</td>
<td>D 613</td>
<td>47 min</td>
<td>47 min</td>
<td></td>
</tr>
<tr>
<td>Cloud point</td>
<td>D 2500</td>
<td>Report²</td>
<td>Report²</td>
<td>ºC</td>
</tr>
<tr>
<td>Carbon residue (g)</td>
<td>D 4530</td>
<td>0.500 max</td>
<td>0.500 max</td>
<td>% mass</td>
</tr>
<tr>
<td>Acid number</td>
<td>D 964</td>
<td>0.50 max</td>
<td>0.50 max</td>
<td>mg KOH/g</td>
</tr>
<tr>
<td>Cold soak flammability</td>
<td>Annex A1</td>
<td>360 max⁺</td>
<td>360 max⁺</td>
<td>seconds</td>
</tr>
<tr>
<td>Free glycerol</td>
<td>D 6554</td>
<td>0.020 max</td>
<td>0.020 max</td>
<td>% mass</td>
</tr>
<tr>
<td>Total glycerol</td>
<td>D 6584</td>
<td>0.240 max</td>
<td>0.240 max</td>
<td>% mass</td>
</tr>
<tr>
<td>Phosphorus content</td>
<td>D 4951</td>
<td>0.001 max</td>
<td>0.001 max</td>
<td>% mass</td>
</tr>
<tr>
<td>Distillation temperature, 90 % recovered</td>
<td>D 1409</td>
<td>360 max</td>
<td>360 max</td>
<td>ºC</td>
</tr>
<tr>
<td>Sodium and Potassium, combined</td>
<td>EN 14536</td>
<td>5 max</td>
<td>5 max</td>
<td>ppm (µg/g)</td>
</tr>
<tr>
<td>Oxidation stability</td>
<td>EN 14112</td>
<td>3 minimum</td>
<td>3 minimum</td>
<td>hours</td>
</tr>
</tbody>
</table>

¹ The test methods indicated are the approved reference methods. Other acceptable methods are indicated in 5.1.
² See X1.3.1. The 8.0 mm²/s upper viscosity limit is higher than petroleum based diesel fuel and should be taken into consideration when blending.
³ Other sulfur limits can apply in selected areas in the United States and in other countries.
⁴ The cloud point of biodiesel is generally higher than petroleum based diesel fuel and should be taken into consideration when blending.
⁵ Carbon residue shall be run on the 100 % sample (see 5.1.11).
⁶ S100 intended for blending into diesel fuel that is expected to give satisfactory vehicle performance at fuel temperatures at or below -12 ºC shall comply with a cold soak flammability limit of 200 s maximum.
2.2 Engine Performance

One of the major benefits of using biodiesel fuels is the fact that it can be used in existing diesel engines. In spite of this, variation in biodiesel feedstock, which leads to variation in fuel properties, could give differences in an engine’s performance (Hansen et al., 2006; Kaufman and Ziejewski, 1984; Moser et al., 1989; Powell, 2007; Sureshkumar et al., 2008). Hence, the next sections would provide more background on biodiesel effects on some of the engine operating characteristics such as net brake power, torque and brake specific fuel consumption.

2.2.1. Net Brake Power and Torque

The net brake power, as defined by the Society of Automotive Engineers (SAE, 2008), is a measure of the engine’s horsepower delivered directly to the engine’s crankshaft without the loss in power caused by the accessories such as the gearbox, alternator, differential, water pump, and other auxiliary components such as power steering pump, muffled exhaust system, etc. Equation 1 shows the relationship between net brake power versus speed and torque.

\[ \dot{W} = 2\pi N \tau \]  

(1)

Where \( \dot{W} \) is the net brake power, kW  
  
  \( N \) is the engine speed, rpm  
  
  \( \tau \) is the Torque, N-m  

The general behavior of an engine’s brake power is to gradually increase to a maximum and then decreases rapidly at an increasing engine speed. This trend is based
on the fact that friction increases with engine speed to a higher power and becomes dominant that it decreases the power at higher speeds.

The net brake power in unmodified diesel engines varies in the literature. Several studies reported that there was a 5% to 10% decrease in engine power when fueling a diesel engine with 100% soybean biodiesel (McDonald et al., 1995; Monyem, 1998; Peterson and Reece, 1996; Schumacher, et al., 2001). With the case of Sureshkumar, et al. (2008), where they use Pongamia pinnata biodiesel, a native oil tree from India, it showed comparable results to petroleum diesel when blends of up to B40 (40% biodiesel and 60% petroleum diesel) were used.

According to Moreno et al. (1999), wherein they fueled a four-cylinder, indirect injected, Isuzu engine with sunflower oil biodiesel, mixtures of 25, 50 and 75% sunflower methyl esters would produce unnoticeable power loss in comparison with diesel fuel. There is even a slight gain which in the case of the mixture of 25% of sunflower biodiesel reaches approximately 3%. They have attributed the power gain on the improvement of fuel spraying in the injectors. Fuel properties such as viscosity and density of the mixture adapted better to the design of the nozzles and needles of the injectors, which facilitates the homogeneity of the fuel with air, and thus improves the combustion process.

Ziejewski and Kaufman (1983), Schumacher et al., (1992), Reece and Peterson (1993), and Marshall (1993) observed reductions in power when using biodiesel ranging from one to seven percent. Schumacher (1992) observed increased power (three percent) using a 1991 Cummins 5.9L DI turbocharged engine. Increased power was observed by
Feldman and Peterson (1992) during a 200 hour EMA test using a 3 cylinder, DI, naturally aspirated diesel engine with the injection timing advanced two degrees.

Torque, on the other hand, is a good indicator of an engine’s ability to do work. It is defined as force acting at a moment distance and has units of N-m or lb-ft. Torque, \( \tau \), is related to work by equation 2.

\[
W_b = 2\pi \tau
\]  

(2)

Where \( W_b \) is the brake work of one revolution

The point of maximum torque is called maximum brake torque speed (MBT). Large engines often have very high torque values with MBT at relatively low speed. Both torque and power are functions of engine speed. At low speed, torque increases as engine speed increases. As engine speed increases further, torque reaches a maximum and then decreases. Torque decreases because the engine is unable to ingest a full charge of air at higher speeds (Pulkrabek, 2004).

2.2.2. Brake-specific Fuel Consumption

Brake specific fuel consumption (BSFC) is a measure of fuel efficiency within the crankshaft of an internal combustion engine (Pulkrabek, 2004). BSFC is defined in equation 3.

\[
\text{bsfc} = \frac{m_f}{W_b}
\]  

(3)

Where \( m_f \) is the rate of fuel consumption of the engine, g/h

\( W_b \) is the net brake power, kW
In relating it with engine speed, BSFC decreases as engine speed increases. It would reach a minimum, and then increases at high speeds. Fuel consumption increases at high speed because of greater friction losses. At low engine speeds, the longer time per cycle allows more heat loss and eventually fuel consumption goes up.

According to Pulkrabek (2004), brake specific fuel consumption generally decreases with engine size, being best (lowest) for very large engines. One reason for this is that large engines have less heat loss due to the higher volume-to-surface-area ratio of its combustion chamber. Also, larger engines operate at lower speeds which reduce friction losses.

With regards to comparing biodiesel with petroleum diesel in terms of BSFC, Ali (1995) tested beef tallow methyl ester and found that there was a 12% to 14% increase in the brake specific fuel consumption when 100% biodiesel was used. Mittelbach and Tritthart (1988) prepared methyl esters from used frying oil and found higher fuel consumption for the ester when compared with standard no. 2 diesel fuel. Other researchers such as Monyem (1998a) and McDonald, et al. (1995), fueled diesel engines with soybean oil methyl ester and standard no. 2 diesel fuel and obtained similar trends.

Moreno et al. (1999) investigated the effects of the percentage of sunflower oil biodiesel in fuel blends on the BSFC. Their findings revealed that an increase in the percentage of biodiesel in a blend would lead to an increase in BSFC. The highest difference they obtained was about 12%. The higher fuel consumption of biodiesel is being attributed to its low heating value, wherein the engine needs more biodiesel to burn in order to produce power comparable to petroleum diesel.
2.3 Exhaust Emissions

Investigations on Environmental Protection Agency regulated exhaust emissions, such as NO\textsubscript{x}, total hydrocarbons (THC), CO, CO\textsubscript{2}, and SO\textsubscript{2} were already being held using different kinds of biodiesel feedstock (Hansen, et al., 2006; McDonald, et al., 1995; Monyem, et al., 1998; Powell, 2007; Schumacher, et al., 2001b; Tat and Van Gerpen, 2003). Biodiesel fuels, regardless of feedstock used, have been observed to reduce most engine exhaust pollutant emissions except for the oxides of nitrogen (NO\textsubscript{x}) wherein it shows higher emissions relative to petroleum diesel.

Nitrogen oxides (NO\textsubscript{x}) collectively refer to both NO and NO\textsubscript{2}. Fundamentally, there are four basic mechanisms that contribute to NO\textsubscript{x} formation: thermal (Zeldovich), prompt, N\textsubscript{2}O, and fuel-bound nitrogen mechanisms (Annamalai and Puri, 2007). The commonly accepted dominant mechanism for fuel-lean and stoichiometric mixtures is thermal dissociation of atmospheric nitrogen; as proposed by Zeldovich, and extended to include combustion-generated hydroxyl radicals (Bowman, 1975). Oxygen concentration and flame temperature influence the NO formation rate (Peterson and Reece, 1996; Stone, 1992).

The increase in NO\textsubscript{x} emissions of biodiesel-fueled diesel engines has long been an issue since the fuel was considered as an alternative to petroleum diesel. In Munoz, et al. (2004), the NO\textsubscript{x} emissions were higher by about 13\% for sunflower methyl ester than those for diesel fuel. Mittelbach and Tritthart (1988) run an engine using methyl esters from used frying oil and measured slightly lower HC, CO, and particulate emissions but
increased NO\textsubscript{x} values. Moreover, according to Munoz et al.(2004) and Grabowski and McCormick (1998), the NO\textsubscript{x} emissions of a diesel engine depends on the engine operation conditions of speed and load as well. Nitrogen oxide emissions tend to increase with reduced engine speed.

According to Stone (1992), hydrocarbon emissions are mostly as a result of flame quenching in an internal combustion engine. There is a narrow quench zone near the cooled cylinder walls that makes the flame go out and the hydrocarbons are not burned. Similar to unburned hydrocarbons, carbon monoxide is produced from partially combusted fuel. Because of this, unburned hydrocarbons and CO are typically very high on cold start due to colder engine parts quenching the flame and preventing complete combustion. Biodiesel will reduce both unburned hydrocarbons and CO compared to diesel in the same engine, under the same conditions (Peterson and Reece, 1996). An emissions study by Munoz et al (2004), however, indicated that improvement in the hydrocarbon emissions is less when the load goes higher.

Oxygenated biofuels have been proven to significantly reduce particulate emissions by providing an increased number of sites for carbon soot oxidation (Luo et al., 1989). Moreover, these oxygenated components can modify the ignition delay period of the combustion by ways not detected with the cetane number. Ignition delay can be a function of both the cetane number and the fuel spray properties (Grabowski and McCormick, 1998).
3. METHODOLOGY

All of the experiments were conducted at the Bio-Energy Testing and Analysis Laboratory (BETA Lab) of the Biological and Agricultural Engineering Department at Texas A&M University. Figure 3 shows the overview of the processes involved in the experiments. Each process is discussed in more detail in the next sections.

Figure 3. Overview of the processes involved in the study.
3.1. Preparation of Vegetable Oils

3.1.1. Extraction of Oils

Oil extraction of locally supplied sunflower, peanuts, and safflower seeds (Producer’s Cooperative, Bryan, TX), were performed in two ways – mechanical and solvent. Both methods were conducted at the BETA Lab. The facility has a small mechanical oil seed press with a rated capacity of 5-8 kg/hr. The oil seed press has extruder diameters ranging from 4.3 mm to 6.2 mm.

Oil extraction was necessary for the said feedstock since biodiesel made out of these feedstock were not readily available in market. Each feedstock was tested with different extruder diameters (i.e. 4.28mm, 5.33 mm, and 6.20 mm) at 140°C. For each test, one kilogram of the sample feedstock was placed in the hopper of the seed press. The starting and end times for mechanical extraction were noted. The weights of the extracted oil and meal were also recorded. The percent oil extracted was calculated using the formula shown in equation 4.

\[
% \text{Oil extracted} = \frac{\text{Wt. of oil extracted}}{\text{Initial Wt. of Sample}} \times 100
\] (4)

Three tests were performed for each feedstock and the averages were determined. The extracted oils were then filtered using a 25 µm filter membrane and prepared for the refining process.

The relationship between percent oil extracted and seed press operating temperature was also developed using shelled peanuts and an extruder diameter of 5.33 mm. Four operating temperatures were chosen at 25°C, 50°C, 100°C, and 140°C.
A solvent extraction set-up was also established for comparison. The solvent used for this study was hexane. Hexane is often used for vegetable oil extraction mainly due to its efficiency and ease of recovery (Akaranta and Anusiem, 1996; Mani et al., 2004). The oil seed press is expected to recover 75% of the oil from the raw materials, while solvent extraction can reach up to 99% oil recovery. The seeds were first ground and weighed with 15 ± 1 g per sample. These samples were then placed inside the cellulose extraction thimbles. The top of each thimble was covered with glass wool, to prevent the sample from floating. A pre-dried flat-bottom extraction flask was weighed and recorded. The oils were extracted with 100 mL of hexane at its boiling point of 69°C for 8 hours in a soxhlet extractor using a heating mantle. The solvent with extracted oil was then cooled. The solvent was removed from the extract through a rotary evaporator at 40°C under reduced pressure (vacuum) of 350 mbar. The final weight of the flask with the extracted oil was determined and recorded. The amount of oil recovered and its percentage in the original sample was calculated and given in equations 5 and 6.

\[
\text{Mass of Oil} = (\text{weight of flask} + \text{extracted oil}) - \text{weight of flask}
\]

(5)

\[
\text{Oil content (\%)} = \frac{\text{mass of oil extracted (g)}}{\text{sample weight (g)}} \times 100
\]

(6)

Three tests were performed for each feedstock and the averages were determined.
3.1.2. Vegetable Oil Refining

The following refining processes were conducted on safflower, sunflower, and peanut oils. Refining procedures that were common on the three feedstocks were degumming, neutralization, dewaxing, and bleaching.

3.1.2.1. Degumming and Neutralization

The extracted oils were heated at 60-70 °C (140-158°F) and de-ionized water (2% of the weight of the oil) was added. The degumming process was enhanced by the addition of phosphoric acid (2% of the weight of the oil). The mixture was agitated for 60 minutes, maintaining a temperature range of 60-70°C (140-158°F). Then, the hydrated gums were removed by centrifugation. For neutralization, the oil was mixed with sodium hydroxide (NaOH) aqueous solution. The amount of NaOH used is based on the free fatty acid content of the sunflower oil. A contact time of 30 minutes was permitted for the formation of soaps. The mixture was then separated using centrifugation. The neutralized oil was washed twice with de-ionized water to ensure the removal of all traces of soap. Oil-water separation was performed using the centrifuge.

3.1.2.2. Dewaxing and Bleaching

The washed neutralized oil was mixed with NaOH aqueous solution (5% of the weight of oil) and de-ionized water (5% of the weight of oil) in covered flasks and placed in a chiller that was set at 5°C. The mixture was agitated for 4 hours. The soapy water wets the waxes which moved from oil to the water phase. The wax was then
removed by centrifugation. Finally, the dewaxed oil was heated to 100°C under constant agitation. Fuller’s earth (activated clay) was added (10% by weight of the oil). Agitation was continued for 30 minutes. The oil was separated from the clay, while its hot, using a centrifuge.

3.2. ASTM Characterization of Biodiesel Fuels

ASTM characterization of the biodiesel was done to ensure that the test fuel used in the study conforms to the ASTM D6751-08 standard (ASTM, 2008). Some of the referenced procedures in the ASTM 6751 standard were conducted in the BETA lab. Such procedures were: cloud and pour point (ASTM D2500), flash point (ASTM D93), water and sediment (ASTM D2709), kinematic viscosity (ASTM D445), acid number (ASTM D664) and gross heating value (ASTM D4809).

3.2.1. Test Fuels

There were a total of six (6) biodiesel test fuels and a reference diesel fuel used for this research. Test fuels such as soybean oil biodiesel (SME), canola oil biodiesel (RME), chicken fat biodiesel (CFME) and ultra low-sulfur diesel, ULSD, reference fuel (REFDIESEL) were bought from commercial producers (New Energy Fuels, Waller, TX; Gulf Hydrocarbon, Inc., Houston, TX; Producer’s Cooperative, Bryan, TX). Other test fuels such as sunflower oil biodiesel (SFME), peanut oil biodiesel (PME), and safflower oil biodiesel (SaffME) were prepared from the previously extracted and refined oils at the BETA Lab. Conventional biodiesel reaction conditions were followed
(reaction time, 1 h; weight of catalyst, 0.4% wt. of initial oil weight; vol. of methanol, 15% vol. of oil; reaction temperature: 50° C). The test fuels were analyzed to determine if they meet ASTM 6751-07 standard. Fuels and fuel blends are as follows:

A. ULSD standard no. 2 reference fuel (REFDIESEL)
B. Soybean oil biodiesel (B5 SME, B20 SME, B50 SME, B100 SME)
C. Canola oil biodiesel (B5 RME, B20 RME, B50 RME, B100 RME)
D. Chicken fat biodiesel (B5 CFME, B20 CFME, B50 CFME, B100 CFME)
E. Sunflower oil biodiesel (B5 SFME, B20 SFME, B100 SFME)
F. Peanut oil biodiesel (B5 PME, B20 PME, B50 PME, B100 PME)
G. Safflower oil biodiesel (B100 SaffME)

3.3. Engine Performance and Exhaust Emissions Testing

Engine performance and exhaust emissions testing were conducted at the BETA Lab engine testing facility. Instrumentation needed to measure some of the EPA regulated emissions, such as CO, CO₂, NOₓ, THC, and SO₂ were in place.

3.3.1. Test Equipment

The BETA lab uses two (2) test engines with their own respective test beds and dynamometer set-ups. One of the test engines was a 3-cylinder Yanmar 3009D diesel engine rated at 14.2 kW (Figure 4). Table 2 lists the general specifications of the small and large test engine. The engine load was controlled by a water-cooled eddy current
absorption dynamometer with a Dynamatic® EC 2000 controller. The maximum braking power of the dynamometer was rated at 22.4 kW (30 hp) at 6000 rpm.

Table 2. General specifications for Yanmar 3009D and JD 4045DF150 diesel engines used.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Yanmar 3009D</th>
<th>JD 4045DF150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>14.2 kW (19hp) @ 3000 rpm</td>
<td>60 kW (80hp) @ 2700 rpm</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Bore</td>
<td>72 mm</td>
<td>106 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>72 mm</td>
<td>127 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.879 L</td>
<td>4.5 L</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>22.6:1</td>
<td>17.6:1</td>
</tr>
<tr>
<td>Combustion system</td>
<td>Indirect injection</td>
<td>Direct Injection</td>
</tr>
<tr>
<td>Aspiration</td>
<td>Natural</td>
<td>Natural</td>
</tr>
</tbody>
</table>

The large test engine used in the study, shown in Figure 5, was an in-line, 4-cylinder, 4.5 L, four stroke, naturally aspirated John Deere diesel engine. It was connected to a 450 HP water-cooled eddy current inductor dynamometer (Pohl Associates Inc., Hatfield, PA). The engine’s rated power was at 80 HP with rated speed of 2500 rpm. The engine’s general specifications were listed in Table 2. The engine load and throttle were controlled by a multi-loop Inter-Loc V dynamometer and throttle controller (Dyne Systems Inc., Jackson, WI).
3.3.2. Instrumentation and Data Acquisition Equipment

Figure 6 shows the schematics of the data acquisition system for the Yanmar 3009D and JD 4045DF150 diesel engines. Instrumentation includes measurement of test cell ambient conditions (barometric pressure, temperature, and humidity), engine speed and torque, fuel flow rates, engine manifold pressures and temperatures, and engine exhaust gaseous emissions measurements. Fuel flow was measured with an AW positive displacement gear type flow meter with 50% ± 1% duty cycle. Manifold pressure measurements were taken by strain gauge pressure transducers positioned in the exhaust and intake manifolds. Temperature measurements were measured with shielded type-K
thermocouples at roughly the same aforementioned locations as pressure. Engine brake torque and speed were acquired from the dynamometer.

Figure 5. JD 4045DF150 diesel engine used for performance and emissions testing.

National Instruments (NI) data acquisition equipment (DAQ) was installed in different parts of the test engines and the test cell. A fiber optic cable connects the remote computer to the NI PCI-7831R FPGA module. Thermocouples and pressure transducers were connected to the SCXI 1320 and SCXI 1326 signal conditioning units. Torque and engine speed data are collected using a NI Labview program developed for this research. Exhaust emissions, such as CO, NO\textsubscript{x}, and SO\textsubscript{2} were measured with
Figure 6. Schematics of the data acquisition system for the Yanmar 3009D and JD 4045DF150 diesel engines.
electrochemical SEM sensors, while CO$_2$ and total hydrocarbons (THC) were measured with NDIR sensors, all assembled in an Enerac™ model 3000E emissions analyzer.

The emissions analyzer has a capability of measuring 0 to 3500 ppm NO$_x$ concentrations, 0 to 2000 ppm CO and SO$_2$ concentrations, with an accuracy of ± 2% of reading; 0 to 5% by volume total hydrocarbon concentrations, and 0 to 20% CO$_2$ concentrations with an accuracy of ± 5% of reading. In addition, it also measures the ambient temperature, stack temperature, stack velocity, and test cell O$_2$ concentrations.

3.3.3. Experimental Method

Engine power tests are conducted in accordance with SAE Standard Engine Power Test Code for diesel engines (SAE J1349 Revised MAR2008). Baseline engine performance and emissions tests are performed using ULSD reference diesel fuel. Engine performance data for ULSD reference diesel were corrected to the standard atmospheric conditions given below.

Compression ignition engine correction formulas as shown (equations 7-13) according to SAE J 1349 – MARCH2008:

\[ B_{p_c} = (CA \times CF) \times B_{p_e} \]  \hspace{1cm} (7)

Where: \( B_{p_c} \) is the corrected brake power

\( CA \) is the Atmospheric Correction Factor, \( CA = (Fa)^{Fm} \)  \hspace{1cm} (8)

\[ Fa = \left( \frac{99}{Fa_{90}} \right)^{a} \left( \frac{T_273}{298} \right)^{b} \]  \hspace{1cm} (9)
Engine Factor, $F_{m} = 0.2$ for $(Q/R) < 37.5$; $R = 1$, $\alpha = 1.0$, $\beta = 0.7$ (for naturally aspirated)

$$Q = 120\ 000 \times \frac{F_{o}}{D \times N}$$  \hspace{1cm} (10)

Where: $F_{o}$ is the observed fuel flow, g/s

$D$ is the engine displacement, L

$N$ is the observed engine speed, min$^{-1}$

$CF$ is the Fuel Correction Factor, $CF = F_{d} \times F_{v}$  \hspace{1cm} (11)

$$F_{d} = 1 + 0.70 \left( \frac{S_{G_{r}} - S_{G_{o}}}{S_{G_{o}}} \right)$$  \hspace{1cm} (12)

$$F_{v} = \frac{1 - S/V_{o}}{1 - S/V_{r}}$$  \hspace{1cm} (13)

Where: $S_{G_{r}}$ is the reference fuel density at 15° C = 0.850 kg/L

$S_{G_{o}}$ is the observed fuel density at 15° C

$F_{v}$ is the fuel viscosity factor

$S = 0.15$ (for pump/line/nozzle systems)

$V_{o}$ is the observed fuel viscosity at 40° C

$V_{r}$ is the reference fuel viscosity at 40° C = 2.6 mm$^{2}$/s

Also, the corrected fuel flow, $F_{c}$, used for the purpose of determining specific fuel consumption, is given by equation 14.

$$F_{c} = \left( \frac{S_{G_{r}}}{S_{G_{o}}} \times F_{v} \right) F_{c}$$  \hspace{1cm} (14)
Variables such as air and relative humidity are carefully monitored. Fuel temperature is controlled as outlined in the test procedure. Tests were conducted in a randomized complete block design (RCBD) to prove that the fuel sequence is not significant to the results of the study. There are two engines (block), six feedstocks (block), five levels of fuel blends (treatments) and 3 replicates of tests (block). Response variables were the following: net brake power (kW), torque (N-m), fuel consumption (L/h), NOx concentrations (ppm), unburned hydrocarbon concentrations (ppm), CO concentrations (ppm), CO₂ concentrations (%), and SO₂ concentrations (ppm). The experimental design lay-out is summarized in Table C.1 of Appendix C.

The BETA lab is equipped with a NI Labview program that can perform remote-based switching of fuel source. This provides changing of test fuels without turning off the engine. At each fuel change, the fuel filter is replaced and then the engine is warmed at idle speed on the new fuel for 15 minutes to purge remaining previous test fuel from the engine’s fuel system. Then, the engine is operated at full throttle and prepared for the next performance testing. Also, a new set of sintered filters for the exhaust emissions analyzer was installed prior to the next emissions testing.

The important sources of uncertainty in this study are: (1) supply of consistent quality of fuel, (2) proper control over relevant engine parameters (e.g. speed and load), and (3) proper use and calibration of the measurement instruments. To minimize the first source of uncertainty, test fuels were processed in such a way that it will match up ASTM 6751 standard. Fresh batch of biodiesel was used to ensure consistency of the fuel quality in the experiment. The uncertainty associated with the second source was
minimized by depending on the proper control and use of engine instrumentation and controller equipment. Parameters, such as engine speed, fuel flow rate, and load accuracy were matched to within ±5 RPM, ±1% of the reading, and ±0.05% of the rated output, respectively. Finally, the uncertainty associated with the third source was minimized by calibrating emissions equipment each day prior to start of testing, and all other instruments (pressure transducers, thermocouples, flow rate meters, etc) on routine basis.

In order to understand the effect of the biodiesel on engine combustion efficiency, the brake specific fuel consumptions (BSFC) for the test fuels and each fuel blend were measured at peak torque condition. This condition was chosen since it is the point of minimum air/fuel ratio and maximum smoke (Canakci and Van Gerpen, 2003). Results were compared to those of the control fuel using statistical analysis procedures (ANOVA and LSD).
4. RESULTS, ANALYSES, AND DISCUSSIONS

4.1. Oil Extraction

Extraction of oils for some of the test fuels (i.e. sunflower, safflower, and peanut) were performed by two means – mechanical and solvent. Oil seed pressing of Peredovik type sunflower (*Helianthus annuus*) seeds, wildlife shelled peanuts (*Arachis hypogaea*), and wild delight safflower (*Carthamus tinctorius* L.) seeds were performed using a small (5-8 kg/hr) mechanical oil seed press. Three sets of tests were performed on each feedstock at different extruder diameters and the averages were determined. These averages were presented in Figure 7. Based on the graph, the recovered oil from sunflower seeds using extruder diameter of 5.33 mm were at 34%, while 37% for shelled peanuts, and 31% from safflower seeds.

![Figure 7](image_url)

Figure 7. Relationship between percent oil extracted and extruder sizes of the three oil seeds (peanut, sunflower, and safflower).
It is important to know that the percent oil recovered was at its highest using extruder #4 with a diameter of 4.28mm. However, it also obtained the longest extraction duration with an average of 30 minutes compared to 25 minutes using extruder #5.

The relationship between percent oil extracted and seed press operating temperature was also developed using shelled peanuts and an extruder diameter of 5.33 mm (Figure 8). Four operating temperatures were chosen (25° C, 50° C, 100° C, and 140° C). Results showed that as the operating temperature is increased, the percent oil extracted also increased. Thirty-five percent (35%) oil was extracted using operating temperatures between 25° C and 100° C and 2% increase was observed between

![Graph showing the relationship between Temperature (°C), % Oil Extraction and duration of extraction (min) using extruder # 5 (5.33mm dia) on shelled peanuts.](image-url)
temperatures 100° C and 140° C. At the same time, extraction duration increases as the extraction temperature is increased. The optimum percent oil extracted of 37% was obtained at 140 °C for 25 minutes.

Extraction using soxhlet procedures was conducted using hexane as solvent. The average oil extracted from sunflower seeds was at the highest with 51%, followed by shelled peanuts with 46%, and 39% from safflower seeds. There is about 8% to 16% difference in percent oil extracted from solvent and mechanical extractions. Solvent extraction definitely extracts more oil from the seeds but requires more time for extraction compared to mechanical means.

4.2. Vegetable Oil Refining

Refining of the previously extracted oils (sunflower, peanut, and safflower) was performed. The refining processes involved were degumming, neutralization, dewaxing, and bleaching. As shown in Figure 9, about 68% of the crude sunflower oil was converted into refined oil. The rest of the percentage was subdivided by the different by-products of each step in the refining process (i.e. 4% gum, 6% soap, 13% wax, and 9% oxidation products). Moreover, 54% of the crude peanut oil was converted into refined oil. The rest of the percentages were at 2% gum, 13% soap, 18% wax, and 13% oxidation products. As for the extracted safflower oil, 70% of it was converted into refined oil. This was about 2% and 16% higher conversion than refined sunflower and peanut oils.
The safflower oil has an acid value of 2.4 mg KOH/g, fairly lower than the peanut oil which has an acid value of 3.6 mg KOH/g. The sunflower oil has the lowest acid value among the three with 1.0 mg KOH/g. The acid value is a measure of how much free fatty acid (FFA) is composed in the oils. Therefore, the higher the acid value of the oil, the higher is its FFA composition. This explains why soap (by-product of neutralization) percentages were higher for peanut oil than safflower and sunflower oils.

Figure 9. Breakdown of the percent composition of (a) safflower oil, (b) peanut oil, and (c) sunflower oil, all showing the by-products of the vegetable oil refining processes.
4.3. ASTM Characterization of Biodiesel Fuels

ASTM characterization of the biodiesel was done to ensure that the test fuels in the study conform to the ASTM D6751-07 standard. Table 3 enumerates the properties of the test fuels. As it was observed from the table, biodiesel made from sunflower and peanut oils did not meet the kinematic viscosity standard (sunflower = 6.3 mm²/s and peanut = 7.0 mm²/s) and may have to require some re-processing or an addition of a fuel additive that can lower its viscosity. Safflower biodiesel was observed to have a very high acid number with 0.68 mm KOH/g compared to the standard limit of 0.5 mm KOH/g. It may require more additional refining or neutralizing steps. The oxidation stability of chicken fat biodiesel is slightly higher than the minimum standard of 3 hrs. The heating values of all biodiesel studied were much lower than petroleum diesel by approximately 10%.

Table 3. Test fuel characteristics as indicated by ASTM 6751 standard.

<table>
<thead>
<tr>
<th>Property</th>
<th>Method</th>
<th>Specification</th>
<th>REF DIESEL²</th>
<th>B100 SME²</th>
<th>B100 RME²</th>
<th>B100 SFME²</th>
<th>B100 Saffme²</th>
<th>B100 PME²</th>
<th>B100 CFME²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash Point, °C</td>
<td>D93</td>
<td>130 min.</td>
<td>128</td>
<td>199</td>
<td>171</td>
<td>192</td>
<td>197</td>
<td>190</td>
<td>131</td>
</tr>
<tr>
<td>Water and Sediment, % vol</td>
<td>D 2709</td>
<td>0.050 max.</td>
<td>&lt;0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Kinematic Viscosity, 40°C, mm²/s</td>
<td>D 445</td>
<td>1.9-6.0</td>
<td>2.3</td>
<td>4.7</td>
<td>4.8</td>
<td>6.3</td>
<td>5.5</td>
<td>7.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Sulfur, ppm</td>
<td>D 5453</td>
<td>15 max</td>
<td>Unknown</td>
<td>4</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>D 613</td>
<td>47 min.</td>
<td>Unknown</td>
<td>55</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>48.2</td>
</tr>
<tr>
<td>Cloud Point, °C</td>
<td>D 2500</td>
<td>Report</td>
<td>-35</td>
<td>-6</td>
<td>-5</td>
<td>2</td>
<td>2</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>
### Table 3 continued.

<table>
<thead>
<tr>
<th>Property</th>
<th>Method</th>
<th>Specification</th>
<th>REF DIESEL&lt;sup&gt;2&lt;/sup&gt;</th>
<th>B100 SME&lt;sup&gt;3&lt;/sup&gt;</th>
<th>B100 RME&lt;sup&gt;2&lt;/sup&gt;</th>
<th>B100 SFME&lt;sup&gt;2&lt;/sup&gt;</th>
<th>B100 Saffme&lt;sup&gt;2&lt;/sup&gt;</th>
<th>B100 PME&lt;sup&gt;2&lt;/sup&gt;</th>
<th>B100 CFME&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Residue, % mass</td>
<td>D 4530</td>
<td>0.050 max.</td>
<td>Unknown</td>
<td>0.01</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>0.02</td>
</tr>
<tr>
<td>Acid Number, mg KOH/g</td>
<td>D 664</td>
<td>0.50 max.</td>
<td>0.04</td>
<td>0.19</td>
<td>0.20</td>
<td>Unknown</td>
<td>0.68</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Distillation temperature, ° C</td>
<td>D 1160</td>
<td>360 max.</td>
<td>Unknown</td>
<td>329</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>352</td>
</tr>
<tr>
<td>Oxidation Stability, hours</td>
<td>EN 14112</td>
<td>3 min.</td>
<td>Unknown</td>
<td>7.2</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>3.3</td>
</tr>
<tr>
<td>Gross Heating Value, Btu/lb</td>
<td>D 4809</td>
<td>Report</td>
<td>18,994</td>
<td>17,242</td>
<td>17,144</td>
<td>16,970</td>
<td>16,962</td>
<td>17,426</td>
<td></td>
</tr>
</tbody>
</table>

1. Analyzed at AAA Chemicals, Shoreacres, TX except for gross heating value, which was analyzed at the BETA Lab
2. Analyzed at the BETA Lab, Texas A&M University
3. Analyzed at Precision Petroleum Labs, Inc., Houston, TX

### 4.4. Engine Performance

#### 4.4.1. Small Engine

The performances of the Yanmar 3009D test engine rated at 19 hp (14.2 kW) at full load (the fuel pump is at the maximum delivery setting) using test fuels, SME, RME, PME, and SFME and its blends were determined in accordance to SAE J1349 Power test code procedures. Except for SFME, all results presented in this research were obtained from the average of three blocks of performance tests for each test fuel. Baseline engine performance and emissions tests were performed using standard no. 2 ULSD fuel. Corrected values of the net brake power and brake-specific fuel consumption for ULSD, as described earlier, were also presented in the following sections.
4.4.1.1. Comparison between Fuel Blends

Soybean Oil Biodiesel (SME). There was no noticeable power loss with the mixtures of 5, 20, and 50% SME, in comparison with REFDIESEL. In fact, there is a slight gain, which in the case of B5 SME, it reaches approximately 1.3%. Figure 10 shows the percentage SME content in a fuel blend in relation to the engine performance parameters (i.e. net brake power, kW; torque, N-m; BSFC, g/kW-h) being investigated. This improvement in net brake power gradually decreases as the percentage of SME increases. The least power gain of 0.2% was observed with B100 SME.

Peak torque was measured from 46.9 N-m for B100 SME to 49.0 N-m for B50 SME at a speed of 2650 rev/min. The highest variation in peak torque values between these fuels was approximately 4.4%. In comparing to REFDIESEL, B100 SME is slightly lower by 3.8%.

The effect of the percentage of SME in a blend on the brake-specific fuel consumption at peak torque conditions was also shown in Figure 9. With the exception of B5 SME, from the figure it can be observed that the BSFC increases as the percentage of SME in the mixture increases. It was approximately 14% higher with neat SME than with pure diesel fuel. Monyem (1998b) and McDonald et al. (1995), obtained 13% to 14% increase in BSFC when they fueled diesel engines with soybean oil biodiesel.
Figure 10. Relationship between engine performance parameters and percentage of soybean oil biodiesel in a fuel blend.
Canola Oil Biodiesel (RME). Figure 11 shows the relationship between maximum net brake power, maximum torque and brake-specific fuel consumption of the Yanmar 3009D test engine with percentage of canola oil biodiesel in a blend. There were no significant differences in peak net brake powers using different blends of canola oil biodiesel compared to REFDIESEL. At peak power speed conditions of 2750 rev/min, the highest net brake power was observed for B20 RME with 13.4 kW. This was about 0.3% higher than REFDIESEL (13.3 kW). B100 RME obtained approximately the same net brake power with 13.3 kW.

There is a slight decrease in peak torque among the RME mixtures compared to REFDIESEL. However, these variations were very small such that the highest variation in peak torque values between fuels and fuel blends was approximately 1.3%, therefore such changes may be considered insignificant.

The BSFC of RME mixtures have the same trend as with the SME mixtures. The BSFC for RME increases as the percent of RME in the mixture increases. The maximum increase was observed with B100 RME with 10.2% higher BSFC than REFDIESEL. As for the other blends, the BSFC’s for B5 RME, B20 RME, and B50 RME were 4.3%, 3.0%, and 4.6% higher than with the REFDIESEL.

Peanut Oil Biodiesel (PME). B50 PME obtained the highest net brake power among the mixtures of PME-diesel fuels being tested (Figure 12). The observed peak power for B50 PME was 2.3% higher than the corrected peak power of pure diesel (13.8 kW vs. 13.5 kW). Other blends such as B5, B20, and B100 have peak power values of 13.5 kW, 13.5 kW, and 13.8 kW, respectively.
Figure 11. Relationship between engine performance parameters and percentage of canola oil biodiesel in a fuel blend.
Figure 12. Relationship between engine performance parameters and percentage of peanut oil biodiesel in a fuel blend.
There was a slight variation in peak torque values for PME-diesel blends compared to REFDIESEL. It is interesting to note that 5, 50, and 100% PME fuels have higher torque values than REFDIESEL. B20 PME obtained the least peak torque value with 47.37 N-m, while B50 PME obtained the highest with 49.9 N-m.

Mixtures of 50% and 100% PME have higher observed readings of BSFC compared to REFDIESEL. B5 and B20 PME were 1.3% and 0.12% less BSFC than pure diesel fuel. REFDIESEL obtained a corrected brake-specific fuel consumption of 270.2 g/kW-h.

Sunflower Oil Biodiesel (SFME). Due to the limited amount of oil extracted from the sunflower seeds to make the sunflower oil biodiesel, data presented was obtained from one set of tests for mixtures of 5, 20, and 100% SFME with REFDIESEL. Figure 13 shows the engine performance parameters in relation to the different mixtures of SFME-diesel fuel. It is interesting to note that there is a slight decrease in power as the percentage of SFME in the mixture increases. The corrected net brake power of REFDIESEL was at 13.95 kW, which is 4.5% higher than the peak net brake power for B100 SFME with 13.3 kW.

The peak torque values for different SFME blends decreased by as much as 2%. Peak torque was measured from 46.0 N-m for B5 SFME to 47.0 N-m for REFDIESEL at a speed of 2700 rev/min. Torque values for B20 SFME and B100 SFME were observed at 46.5 N-m and 46.4 N-m, respectively.
Figure 13. Relationship between engine performance parameters and percentage of sunflower oil biodiesel in a fuel blend.
The brake-specific fuel consumption at peak torque conditions was also determined. There was a noticeable loss in BSFC when B5 SFME and B20 SFME were used compared to REFDIESEL. However, the BSFC gained up to 6% when fueling with B100 SFME. In a study by Moreno et al. (1999), wherein they fueled a four-cylinder, turbocharged, indirect injected Isuzu engine with 100% SFME, the BSFC increased at approximately 12% higher than with pure diesel fuel.

4.4.1.2. Comparison between Biodiesel Feedstock

As for the comparison between biodiesel feedstock, Figure 14 shows the performance curves for the diesel engine using standard no. 2 ULSD fuel (REFDIESEL), B100 SME, B100 RME, B100 PME, and B100 SFME, respectively. For REFDIESEL, the corrected peak brake power is at 13.5 kW (18.0 hp) at an engine speed of approximately 2940 rev/min. Similar results were obtained using B100 SME. The net brake power for B100 PME was 2% higher than REFDIESEL with 13.7 kW. Other test fuels (i.e. B100 RME and B100 SFME) are 1% lower than REFDIESEL with both fuels obtaining 13.3 kW.

Figure 15 shows the plot of the brake-specific fuel consumption (BSFC) of different test fuels and reference fuel at different engine speeds. At peak torque conditions, all of the test fuels obtained higher BSFC’s compared to the reference fuel. B100 SME, B100 RME, B100 PME, and B100 SFME, are 14%, 10%, 9%, and 5% higher than REFDIESEL.
The Analysis of Variance (ANOVA) statistical technique was used to determine the variation in BSFC’s among the four test fuels (Table 4). Using $\alpha = 0.05$, results indicated that there is a significant difference between the BSFC’s of the test fuels at peak torque conditions with a p-value of zero. Fisher’s least significant distance (LSD) method was then used to determine specifically which fuels were significantly different from one another. Table 5 shows the results of the statistical procedure. The results from Fisher’s LSD verified that REFDIESEL is significantly different from the biodiesel fuels. B100 SME and B100 SFME are in the same group, meaning the two test fuels will have the same averages of BSFC when the engine is loaded at peak torque conditions.
The other two test fuels, B100 RME and B100 PME, individually have their own BSFC range.

Figure 15. Relationship between brake-specific fuel consumption (g/kW-h) and engine speed using test fuels B100 SME, B100 RME, B100 PME, and B100 SFME, and reference fuel REFDIESEL. Data were taken from the Yanmar engine described earlier.

Table 4. Analysis of variance for the BSFC at peak torque conditions of the four test fuels.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>5327.576</td>
<td>4</td>
<td>1331.894</td>
<td>179.152</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Within Groups</td>
<td>74.344</td>
<td>10</td>
<td>7.434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5401.920</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Results of the Fisher’s LSD statistical method on the BSFC of the four test fuels and reference diesel fuel.

<table>
<thead>
<tr>
<th>(I) FUEL</th>
<th>(J) FUEL</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
<th>Upper Bound</th>
<th>Lower Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REF-DIESEL</td>
<td>SME</td>
<td>-38.30311(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>-43.2636</td>
<td>-33.3427</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RME</td>
<td>-53.66400(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>-58.6244</td>
<td>-48.7036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PME</td>
<td>-19.03722(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>-23.9977</td>
<td>-14.0768</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SFME</td>
<td>-41.30561(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>-46.2661</td>
<td>-36.3452</td>
<td></td>
</tr>
<tr>
<td>SME</td>
<td>REF-DIESEL</td>
<td>38.30311(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>33.3427</td>
<td>43.2636</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RME</td>
<td>-15.36089(*)</td>
<td>2.22627</td>
<td>&lt;0.001</td>
<td>-20.3213</td>
<td>-10.4004</td>
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* The mean difference is significant at the .05 level.

4.4.2. Large Engine

The performance curves of JD 4045DF150 diesel engine with power rating of 60 kW (80 hp) were determined for SME, RME, PME, SaffME, SFME, and CFME test fuels. Only four (i.e. SME, RME, PME, and CFME) test fuels were tested for blends comparison due to the limitedness of the seeds from the other two test fuels (i.e. SaffME, SFME). However, we were able to conduct three tests for each test fuel. The results of the three replications were averaged and reported.
4.4.2.1. Comparison between Fuel Blends

**Soybean Oil Biodiesel (SME).** There was a slight loss of power for B5 SME compared to REFDIESEL (Figure 16). B5 SME has 1.2% less power than REFDIESEL (55.65kW). An improvement was then seen as the percentage of SME was increased to 20% SME and 80% ULSD fuel. B20 SME obtained the highest peak power of 56.46 kW, which was 1.46% higher than REFDIESEL. However, this improvement gradually diminishes as the percentage of SME in the blend was increased. A slight loss in power was observed for B100 SME with 54.6 kW.

There was no noticeable change in maximum torque for all fuel blends of SME and standard no. 2 ULSD fuel. The highest variation of peak torque to REFDIESEL was observed with B20 SME. It was 1.8% higher than REFDIESEL.

A general trend was observed for BSFC of SME and its blends. As the percentage of SME was increased in a blend, the BSFC also increases. Although B5 SME and B20 SME obtained lower BSFC’s than REFDIESEL, with 1.2% and 2% lower BSFC, it was still considered insignificant differences. A 17.2% increase in BSFC was observed from B100 SME compared to REFDIESEL.

**Canola Oil Biodiesel (RME).** Figure 17 shows the effects of the percentage of RME in a mixture on net brake power, maximum torque and brake-specific fuel consumption of the JD 4045DF150 diesel test engine. B50 RME obtained the least peak power at 55.3 kW, while B20 RME obtained the highest peak power at 56.2 kW. Although there was slight differences in the peak net brake powers of the fuel blends, it
Figure 16. Relationship between engine performance parameters and percentage of soybean oil biodiesel in a fuel blend. Data were taken from JD 4045DF150 engine.
was still considered insignificant since there was only an approximately 2% difference between the fuel blends.

Similar trends were seen in the peak torque values. B20 RME obtained the highest peak torque value with 295.0 N-m, while B50 RME obtained the least peak torque value with 291.4 N-m. Again, the differences are very minimal, therefore any differences were considered insignificant.

The BSFC at peak torque conditions, on the other hand, have interesting results. All the test fuel obtained higher BSFC’s than REFDIESEL. The mixtures of 5, 20, 50, and 100% RME with pure diesel were 10%, 12%, 12%, and 9% higher BSFC’s compared to REFDIESEL.

**Peanut Oil Biodiesel (PME).** The trend for the net brake power of PME was similar to the one with SME as shown in Figure 18. There was a slight loss of power for B5 PME compared to REFDIESEL. B5 PME has 0.81% less power than REFDIESEL (55.7 kW). An improvement was also observed as the percentage of PME was increased to 50% peanut oil biodiesel and 50% diesel fuel. B50 PME obtained the highest peak power of 55.9 kW, which was 1% higher than REFDIESEL (not significant). However, this improvement gradually disappears as the percentage of PME in the blend was increased to B100 PME. A slight loss in power was observed for B100 PME with 54.8 kW.
Figure 17. The effects of the RME fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption.
Figure 18. The effects of the peanut oil biodiesel fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption.
The peak torque values for most of the PME blends increased by as much as 2%. Peak torque was measured from 287.1 N-m for B5 PME to 294.5 N-m for B50 PME at a speed of 800 rev/min. Torque values for B20 PME and B100 PME were observed at 289.3 N-m and 289.8 N-m, respectively.

The effect of the percentage of PME in a blend on the brake-specific fuel consumption at peak torque conditions was also shown in Figure 18. From the figure it can be observed that the BSFC increases as the percentage of PME in the mixture increases. It was approximately 19% higher with neat SME than with pure diesel fuel. B50 PME obtained the highest BSFC with 325.3 g/kW-h, compared to 248.8 g/kW-h for REFDIESEL.

Chicken Fat Biodiesel (CFME). Figure 19 shows the engine performance parameters in relation to the different mixtures of CFME-diesel fuel. It is interesting to note that there is a slight decrease in power as the percentage of CFME in the mixture increases. The observed net brake power for B100 CFME was at 53.4 kW, which is 4.0% lower than the corrected peak net brake power for REFDIESEL with 55.7 kW.

A slight increase in peak torque as the percentage of chicken fat biodiesel was increased in the fuel blend. The peak torque was observed at its highest from B5 CFME with 291.4 N-m. Peak torque values gradually decrease as the percent of CFME in the blend increase. B100 CFME obtained the least peak torque at 281.9 N-m.

Generally, the BSFC for CFME increases as the percent of CFME in the mixture increases. The maximum increase was observed with B100 CFME with 12% higher BSFC than REFDIESEL. Less BSFC was observed for B5 CFME with 247.6 g/kW-h,
compared to 248.8 g/kW-h for REFDIESEL. As for the other blends, the BSFC’s for B20 CFME, and B50 CFME were 11%, and 7% higher than with the REFDIESEL.

4.4.2.2. Comparison between Biodiesel Feedstock

Figures 20 and 21 show the performance curves of the test engine using REFDIESEL, B100 SME, B100 RME, B100 SFME, B100 PME, and B100 CFME. The corrected peak net brake power using REFDIESEL was observed to be the highest compared to the biodiesel fuels. Percent differences in peak net brake power were from 0.2% to 2%.

Moreover, the peak torque value for REFDIESEL was higher than peak torque values for biodiesel fuels. 293.2 N-m at 770.3 rev/min was observed for REFDIESEL, while 289.8 N-m at 868.5 rev/min, 284.8 N-m at 825.5 rev/min, 293.9 N-m at 869.8 rev/min, 289.6 N-m at 847.3 rev/min, 289.1 N-m at 868.2 rev/min, and 288.7 N-m at 854 rev/min, were observed for B100 PME, B100 CFME, B100 RME, B100 SaffME, B100 SFME, and B100 SME, respectively.

Differences in brake specific fuel consumption were also significant among the reference fuel and the biodiesel fuels (Figure 22). At peak torque conditions, B100 SaffME obtained the highest BSFC with 314.78 g/kW-h, while REFDIESEL obtained the lowest with 248.78 g/kW-h.
Figure 19. The effects of chicken fat biodiesel fuel percentage on engine performance parameters’ net brake power, torque, and brake-specific fuel consumption.
Figure 20. Net brake power (kW) versus engine speed of JD 4045DF150 diesel engine using REFDIESEL and test biodiesel fuels.

Figure 21. Torque produced (N-m) versus engine speed (rpm) of JD 4045DF150 diesel engine using REFDIESEL and test biodiesel fuels.
The Analysis of Variance is summarized in Table 6. With a p-value of approximately zero means that there is a significant difference in the brake-specific fuel consumption of the engine using different biodiesel fuels at peak load conditions. Furthermore, Fisher’s LSD results indicated that there is no strong evidence of differences among SME, SFME and PME test fuels (Table 7).

Figure 22. Plot of the brake specific fuel consumption (g/kW-h) against engine speed (rpm). Data taken from JD 4045DF150 diesel engine tests.
Table 6. Analysis of variance for the BSFC of JD 4045DF150 using six types of biodiesel fuels.

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<th>Sources of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
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<th>P-value</th>
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Table 7. Results of the Fisher’s LSD statistical method on the BSFC of the four test fuels and reference diesel fuel.

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<th>Sig.</th>
<th>95% Confidence Interval</th>
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* The mean difference is significant at the .05 level.

4.4.3. Summary

Two objectives have been achieved in this section: 1) The relationships between the characteristic engine performance (i.e. brake horsepower, torque and specific fuel consumption) and the percentages of biodiesel in fuel blends were determined; and 2) The differences in engine performance between different biodiesel feedstock under study (i.e. soybean oil, canola oil, sunflower oil, safflower oil, peanut oil, and chicken fat) were assessed.

Two test fuels, SFME and RME, delivered less power in reference to pure diesel fuel when used in a 3-cylinder Yanmar diesel engine, while CFME tends to perform the same for JD 4045DF150 engine. Power is a function of the engine geometry, speed, air/fuel ratio, efficiencies and fuel properties. Assuming mechanical losses are similar,
and since there were no modifications made in the injection rates or duration for an individual test fuel, power loss may be attributed to the variation in the fuel properties such as heating values and densities between fuels.

Moreover, the rise in mass flow for all biodiesel fuels as observed from both engines can be attributed to the differences in the heating values of the test fuels. The biodiesel fuels have approximately 10% lower heating values than the reference diesel. The heating value affects the torque being produced and in order to match that torque with REFDIESEL, pure biodiesel (i.e. SME, RME, SFME, SaffME, CFME, and PME) and its blends with REFDIESEL will have to put more energy in the engine, resulting to higher fuel consumption. Also, as far as engine performance is concerned, it was determined based on the statistical analyses performed on BSFC at peak torque conditions for both engines that the BSFC’s of 100% SME and SFME were statistically the same.

Finally, the data presented in this section verified that biodiesel may be used as a supplemental fuel for steady-state non-road diesel engines. When using small percentage of fuel blends, such as B5 and B20, peak power and BSFC were not significantly different from that of pure diesel fuel. Hence, consumers may elect to use these blends in order to take advantage of the lubricity of biodiesel as well as contributing to the goal of lowering the dependence to petroleum diesel.
4.5. Exhaust Emissions

4.5.1. Small Engine

Some of the EPA regulated emissions determined in this research were CO, CO₂, NOₓ, SO₂, and total hydrocarbons. The Enerac 3000E exhaust emissions analyzer was used for the emissions testing. Data presented in this section are the averages of three readings for SME, PME, and RME and its blends with REFDIESEL, and a single reading for SFME and its blends with REFDIESEL fuel.

4.5.1.1. Comparison between Fuel Blends

**Peanut Oil Biodiesel (PME).** The emission concentrations for PME and its blends at peak torque conditions are shown in Figure 23. From the figure, it can be observed that NOx and CO₂ emissions increase as the percentage of PME biodiesel in a blend is increased. The minimum emission of NOx takes place when using a mixture of 5% PME with diesel fuel. The NOx emission in this case diminishes by 5%. REFDIESEL produced the least CO₂ with 7%. When using pure PME, NOx and CO₂ emissions increased by approximately 30% and 18%, respectively.

As for other emissions, CO concentration data were similar to that reported in the literature (Schumacher et al., 2001). CO emission increases as the percentage of PME in the blend increases. A decrease of 29% in CO concentrations where observed as the mixture increase from 0 to 50% PME fuel. Likewise, there were no noticeable differences in the SO₂ concentrations produced using PME and its blends with REFDIESEL. At peak torque conditions, the SO₂ concentrations stayed below 10 ppm
levels. Finally, THC concentrations increased by as much as 30% from using pure diesel (10.78 ppm) to B100 PME (14 ppm).

**Sunflower Oil Biodiesel (SFME).** The trends observed concerning NOx emissions while testing the Yanmar engine clearly indicated that as the level of SFME in the blend increased, NOx emissions levels emitted by the engine also increased (Figure 24). With pure SFME the emission of NOx is 34% higher than that of REFDIESEL. Moreno et al. (1999), however, reported that the NOx emission of a four cylinder, turbocharged, indirect-injected Isuzu engine using B100 SFME is only 5% higher than that of diesel fuel. It is interesting to note that the viscosity and density of the feedstock used in the literature were at 4.1 mm²/s and 0.9 kg/L. According to Moser et al. (1989), the higher density and viscosity of the biodiesel imply that the differential pressure at the advance piston contained in the distributor pump is slightly increased, which in turn advances injection. The viscosity and density of SFME for this study, however, were at 6.3 mm²/s and 0.9 kg/L. This variation in the viscosities may have influenced the NOx concentration through the advancing of the injection timing.

Carbon dioxide emission, on the other hand, had its peak at 20% SFME and gradually decrease as the percentage of SFME in blend is increased. With B100 SFME, the CO₂ emission was 14% higher than pure diesel. Similar trends were observed for THC concentrations. It peaks at B20 SFME and then gradually decreases as it reach B100 SFME. The increase in THC concentrations from REFDIESEL to 100% SFME
Figure 23. Effects of peanut oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the Yanmar diesel engine.
Figure 24. Effects of sunflower oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the Yanmar diesel engine.
was approximately 32%. Finally, the emission of carbon monoxide in the outlet gases decreases as the content of SFME increases. It reaches a minimum at 20% SFME. Then CO emission gradually increases as the percent of SFME reaches 100%.

4.5.1.2. Comparison between Biodiesel Feedstock

The NOx concentrations of the Yanmar 3009D test engine using different biodiesel fuels were shown in Figure 25. Generally, all biodiesel fuels under study have higher NOx concentrations than the reference fuel. However, NOx from PME was observed to be the most comparable to REFDIESEL.

![Figure 25](image.png)

Figure 25. Oxides of nitrogen (NOx) concentrations of Yanmar 3009D diesel engine using ULSD (standard no. 2) fuel and biodiesel test fuels.
Other EPA regulated exhaust emissions such as CO, CO$_2$, total hydrocarbons, and SO$_2$, were also measured (Figure 26). Generally, the trend for CO and CO$_2$ concentrations tends to be decreasing as the engine speed is increased. REFDIESEL, as expected, has higher CO concentrations than the biodiesel fuels. Total hydrocarbon concentrations seemed to be not affected by the engine speed. Finally, SO$_2$ emissions for all test fuels were observed to be lower than the 15-ppm limit imposed by EPA regulations.

4.5.2. Large Engine

4.5.2.1. Comparison between Fuel Blends

Soybean Oil Biodiesel (SME). B100 SME obtained the highest NOx concentration among the mixtures of SME-diesel fuels being tested on the JD 4045DF150 engine (Figure 27). The observed NOx concentration for B100 SME (522 ppm) was 18.4% higher than the NOx concentration of pure diesel (441 ppm). Other blends such as B5, B20, and B50 have NOx concentration values of 461 ppm, 437 ppm, 514 ppm, respectively.

In addition, there was a slight variation in THC concentration values for SME-diesel blends compared to REFDIESEL. It is interesting to note that 5, 50, and 100% PME fuels have higher THC concentration values than REFDIESEL. B20 SME obtained THC emissions of 15 ppm, while B50 PME obtained the highest with 26 ppm. Also, there were no traces of SO$_2$ concentration that was observed in the exhaust for all SME fuel blends.
Figure 26. Carbon dioxide (CO2), carbon monoxide (CO), total hydrocarbon (THC) and sulfur dioxide (SO2) concentrations of Yanmar 3009D diesel engine using ULSD (standard no. 2) and biodiesel test fuels.
However, it is interesting to note that there is a slight decrease in CO emissions as the percentage of SME in the mixture increases. This trend is similar to the CO emissions when PME and SFME were used in the engine. The CO emission for REFDIESEL was at 138 ppm, which is 60% higher than the CO emission for B100 SME with 55 ppm.

Finally, the effect of the percentage of SME in a blend on the CO\textsubscript{2} emissions at peak torque conditions was also determined. A sudden increase in CO\textsubscript{2} emissions was observed from 0% SME to 5% SME. However, it gradually decreases as the percentage of SME in a blend is increased from 5% to 100%. B100 SME has approximately 2% lower CO\textsubscript{2} emissions than with pure diesel fuel.

**Canola Oil Biodiesel (RME).** Other than B5 RME, a steady increase in NOx concentrations has been seen as the percentage of canola oil biodiesel in a blend is increased (Figure 28). The NOx concentration for B100 RME was about 38.1% higher than with the REFDIESEL. As for the CO concentrations, it shows a similar trend with SME. As the percentage of RME increases, the CO emission decreases. A 45% deduction in CO concentration was observed for B100 RME.

There was a slight variation in THC and CO\textsubscript{2} concentrations for RME-diesel blends compared to REFDIESEL. All blends produced higher THC and CO\textsubscript{2} concentrations than REFDIESEL. B5 RME produced the highest CO\textsubscript{2} and THC.
Figure 27. Effects of soybean oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine.
concentrations with 8.25% and 22.5 ppm. REFDIESEL, on the other hand, REFDIESEL produced 6.4% CO$_2$ and 15 ppm THC concentrations. Lastly, SO$_2$ concentrations were low for all test fuels. The maximum SO$_2$ concentration was observed from B5 and B50 RME, each with 3 ppm of sulfur dioxide concentrations released.

**Peanut Oil Biodiesel (PME).** Figure 29 shows the effects of the increase in PME in a mixture on some of the EPA regulated emissions. As expected and as what was observed in the small engine, the CO concentration for the large engine decreases as the percentage of PME in fuel blend is increased. The lowest CO concentration was observed with B50 PME at 98 ppm, while B100 PME (8% higher than B50 PME) has 109 ppm of CO concentrations.

The emissions of NOx concentrations for PME mixtures have the same trend as with the SME and RME test fuels. The NOx concentration for PME increases as the percent of PME in the mixture increases. The maximum increase was observed with B100 PME with 18% higher NOx concentrations than REFDIESEL. As for the other blends, the NO concentrations for B5 PME, B20 PME, and B50 PME were 10%, 7%, and 5% higher than with the REFDIESEL.

THC and CO$_2$ concentrations have similar trends. An increase in THC and CO$_2$ concentrations was observed with B5 PME from REFDIESEL and then it gradually diminishes as the percent of PME in the blend is increased. SO$_2$ concentrations, on the other hand, do not seem to be affected in the changes in percentage of PME in the test fuel.
Figure 28. Effects of canola oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine.
Figure 29. Effects of peanut oil biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine.
**Chicken Fat Biodiesel (CFME).** Figure 30 shows the percent CFME content in a fuel blend in relation to the engine performance parameters (i.e. net brake power, kW; torque, N-m; BSFC, g/kW-h) being investigated. As for the NOx emissions, blends of 50% and 100% CFME have higher observed readings of NOx concentrations compared to REFDIESEL. B5 and B20 CFME produced 6% and 3% less NOx emissions than pure diesel fuel. B100 CFME produced 12% higher NOx emissions than REFDIESEL.

Also, a general trend of decreasing THC, SO$_2$ and CO concentrations were observed as the percentage of CFME in the blend is increased. The minimum THC, SO$_2$ and CO concentrations were observed from B100 CFME.

Finally, the effect of the percentage of CFME in a blend on the CO$_2$ concentrations at peak torque conditions was also determined. A gradual increase in CO$_2$ emissions was observed from 0% CFME to 50% CFME. However, it gradually decreases as the percentage of CFME in the blend is increased from 50% to 100%. B100 CFME has approximately 9% higher CO$_2$ emissions than with pure diesel fuel.

4.5.2.2. Comparison between Biodiesel Feedstock

Figure 31 shows the NOx emissions of the test engine at speeds between 800 rev/min and 2700 rev/min using the six biodiesel test fuels. Generally, NOx emissions tend to decrease as the speed of the engine is increased. Peak NOx emissions were observed a little above peak torque speeds for all test fuels. B100 RME obtained the highest peak NOx concentrations with 627 ppm at 869.8 rev/min. REFDIESEL obtained the lowest peak NOx concentrations with 454 ppm at 1203 rev/min.
Figure 30. Effects of chicken fat biodiesel fuel percentage on different exhaust emissions. Data were taken from the JD 4045DF150 diesel engine.
Figure 31. Oxides of nitrogen (NOx) concentrations of JD 4045DF150 diesel engine using ULSD standard no. 2 diesel and test biodiesel fuels.

Carbon monoxide, carbon dioxide, and total hydrocarbon concentrations for biodiesel fuels were relatively higher than REFDIESEL (Figure 32). CO$_2$ concentrations tend to gradually increase as the speed increases, however, up to a certain point (2050 rev/min). Afterwards, CO$_2$ concentrations tend to decrease rapidly up to peak power conditions. On the other hand, carbon monoxide, sulfur dioxide and total hydrocarbon concentrations tend to peak as it approaches peak power conditions.
Figure 32. Carbon dioxide (CO2), carbon monoxide (CO), total hydrocarbon (THC) and sulfur dioxide (SO2) concentrations of JD 4045DF150 diesel engine using ultra-low sulfur (standard no. 2) farm diesel and test biodiesel fuels.
4.5.3. Summary

The following objectives were accomplished in this section: 1) The relationship between pollutant concentrations (i.e. NOx, SO2, THC, CO and CO2) in a diesel engine exhaust and the percentage of biodiesel in fuel blends were determined; and 2) The differences in exhaust emissions between different biodiesel feedstock under study (i.e. soybean oil, canola oil, sunflower oil, safflower oil, peanut oil, and chicken fat) were evaluated.

Generally, total hydrocarbon emissions were higher in fuel blends such as B5 and B20 and then gradually decreases as the percentage of biodiesel in a fuel blend was increased to B100. This trend was exemplified by all of the test fuels in both small and large engines. Also, carbon monoxide concentrations for all biodiesel test fuels and its blends were lower than the REFDIESEL. The reduction of both HC and CO emissions may be attributed as a result of having high density, viscosity and oxygen content levels for biodiesel fuels. An increase in the viscosity of the fuel produces a greater advance in the injection timing; however, this effect is lower in high engine speeds (Moser et al., 1989).

The viscosity of SFME and PME are very high. Both fuels did not meet the ASTM 6751 standard for kinematic viscosity (D 445). The higher density and viscosity of SFME and PME imply that the fuel pump pressure is slightly increased, which in turn advances the injection. An increment of the density and viscosity in the fuel implies a change in the characteristics of the fuel jet liberated by the injector (size of droplets, penetration, etc.), not to mention increasing the amount of fuel retained in the interior of
the injector nozzle. This retained fuel suffers a delay in its incorporation inside the combustion chamber, and this produces an increase in the hydrocarbons without burning (Munoz et al., 2004).

In addition, Rakopoulos et al. (1996) have concluded in their research work that in the case of using pump-line-nozzle injection systems, both HC and CO emissions decrease as the oxygen in the combustion chamber increases. Sources of oxygen can either be with oxygenated fuels such as biodiesel or oxygen-enriched air.

Carbon dioxide concentrations were observed to be higher at low engine speeds and high load. This trend has been observed for both engines. The percentage of biodiesel in the blend also describes that CO$_2$ emissions are its highest on blends between B5 and B20, and then gradually decreases as the percentage of biodiesel is increased to 100%.

The Nitrogen oxide emissions are clearly dependent on engine speed and load. NOx emission is increased at reduced engine speed. Also, the higher the percentage of biodiesel in the blend would result to the higher production of NOx in the exhaust. Higher viscosities for biodiesel fuels, which would result to the advancing of the injection timing, may also be attributed to the increase in NOx concentrations. The fuel spray properties could change such that the increase in the droplet sizes could reduce the fraction of burned fuel in the pre-mixture phase (ignition delay period), which means an increase in the duration of the diffusive phase (Grabowski and McCormick, 1998).

Lastly, SO$_2$ concentrations were very low for all test fuels, including the ultra-low sulfur reference diesel fuel. SO$_2$ emissions hardly pass the 15 ppm mark.
5. SUMMARY AND CONCLUSIONS

When new feedstocks are identified, the criteria should be whether the feedstock will produce biodiesel that will easily comply with the ASTM standards upon refining and conventional biodiesel processing. Biodiesel producers must realize that each feedstock has different properties that would impact refining ability as shown in this study. For example, sunflower and peanuts have high wax content (13% and 18%, respectively) and producers must be aware of yield reduction during refining process. Other feedstocks have high acid number (e.g., 0.68 for safflower vs. the standard 0.5) and may require additional refining or neutralizing steps. Still others will have high kinematic viscosity values (sunflower = 6.3 mm$^2$/s and peanut = 7.0 mm$^2$/s) that are higher than the standard (6.0 mm$^2$/s) and will require additives to bring kinematic viscosity to within the standard limit. New feedstock will have to undergo various refining and trans-esterification studies before they can qualify as commercial grade biodiesel. Chicken fat has potential as biodiesel after proper refining.

The engine performance tests show that an engine operating on biodiesel generates a slightly less power and torque at any given speed than that fueled by diesel without taking into account the lower heating value of the biodiesel fuel. Biodiesel has about 10% less energy than diesel and the reduction in torque and power is at most 8% for small engines and 2% for large engines. The lower heating value of biodiesel fuel is reflected in the specific fuel consumption, i.e., to generate the same power, more biodiesel is needed. Thus, as much as 19% more biodiesel is required for some feed
stocks (SaffME) to as low as 8% for some (RME) to achieve the same power output. The reduction in torque and power of less than 10% indicates that in some cases, biodiesel has better combustion than diesel. Unfortunately, this characteristic high combustion efficiency may give rise to increased combustion temperature which may lead to higher NOx emissions.

Total hydrocarbon and CO$_2$ emissions were higher in fuel blends such as B5 and B20 and then gradually decreases as the percentage of biodiesel in a fuel blend was increased to B100. This trend was exemplified by all of the test fuels in both small and large engines. Also, carbon monoxide concentrations for all biodiesel test fuels and its blends were lower than the REFDIESEL. The reduction of both THC and CO emissions may be attributed to the high density, viscosity and oxygen content levels of biodiesel fuels.

The engine NOx exhaust emission for most biodiesel fuel is on the average higher than reference diesel. However, this is not true for all rpm and load conditions. For small engines, higher NOx emissions were seen at all rpm, but for large engines, there are load conditions and rpm level where the NOx emissions for biodiesel and blends are lower. Generally, NOx are higher at low speed conditions. As the engine approaches peak power, NOx emissions for biodiesel fuels and large engines are almost the same as reference diesel. At even higher speeds, biodiesel NOx emissions may in fact be lower.

In conclusion, this study has shown that NOx emissions are higher, particularly at low speeds for most biodiesel and blends and may require some additives or engine
modifications/or adjustments to equal the NOx emissions of diesel. Other emissions particularly SO₂ are very for both diesel and biodiesel fuels. It was also shown (based on exhaust emissions profile) that biodiesel fuels have better combustion behavior than diesel at lower engine speeds based on higher concentrations of combustion products such as CO₂.
REFERENCES


### APPENDIX A

#### Table A.1. SME Blends comparison using the Yanmar 3009D diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFDIESEL</td>
<td>13.43*</td>
<td>2941.81</td>
<td>48.73</td>
<td>2607.78</td>
<td>285.55*</td>
<td>275.00*</td>
</tr>
<tr>
<td>B5 SME</td>
<td>13.61</td>
<td>2754.97</td>
<td>47.17</td>
<td>2754.97</td>
<td>274.26</td>
<td>274.26</td>
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<tr>
<td>B20 SME</td>
<td>13.58</td>
<td>2898.50</td>
<td>47.37</td>
<td>2631.79</td>
<td>283.75</td>
<td>288.78</td>
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<td>B50 SME</td>
<td>13.60</td>
<td>2896.31</td>
<td>49.03</td>
<td>2484.56</td>
<td>287.55</td>
<td>283.41</td>
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<td>B100 SME</td>
<td>13.45</td>
<td>2918.34</td>
<td>46.89</td>
<td>2534.03</td>
<td>307.67</td>
<td>313.86</td>
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</tbody>
</table>

* Corrected as described in SAE J 1349.

#### Table A.2. RME Blends comparison using the Yanmar 3009D diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
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<tr>
<td>REFDIESEL</td>
<td>13.33*</td>
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<td>B5 RME</td>
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<td>2744.74</td>
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<td>267.84</td>
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<td>B20 RME</td>
<td>13.36</td>
<td>2747.44</td>
<td>46.44</td>
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<td>270.25</td>
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<td>B50 RME</td>
<td>13.34</td>
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<tr>
<td>B100 RME</td>
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<td>303.96</td>
<td>308.38</td>
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* Corrected as described in SAE J 1349.
### Table A.3. SFME Blends comparison using the Yanmar 3009D diesel engine.

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<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
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<tr>
<td>REF-DIESEL</td>
<td>13.95*</td>
<td>2911.43</td>
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<td>B5 SFME</td>
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<td>2957.14</td>
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* Corrected as described in SAE J 1349.

### Table A.4. PME Blends comparison using the Yanmar 3009D diesel engine.

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<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
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<tr>
<td>REF-DIESEL</td>
<td>13.47*</td>
<td>2941.81</td>
<td>48.73</td>
<td>2607.78</td>
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<tr>
<td>B5 PME</td>
<td>13.52</td>
<td>2951.33</td>
<td>49.52</td>
<td>2613.04</td>
<td>272.25</td>
<td>266.64</td>
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<tr>
<td>B20 PME</td>
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<td>2934.34</td>
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<td>B100 PME</td>
<td>13.74</td>
<td>2937.61</td>
<td>49.60</td>
<td>2628.00</td>
<td>292.31</td>
<td>294.60</td>
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* Corrected as described in SAE J 1349.
### Table A.5. CFME Blends comparison using the JD 4045DF150 diesel engine.

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<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
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<td>Refdiesel</td>
<td>55.65*</td>
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<td>B50 CFME</td>
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<td>2371.00</td>
<td>281.90</td>
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<td>276.79</td>
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* Corrected as described in SAE J 1349.

### Table A.6. SME Blends comparison using the JD 4045DF150 diesel engine.

<table>
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<tr>
<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refdiesel</td>
<td>55.65*</td>
<td>2493.00</td>
<td>288.30</td>
<td>1002.00</td>
<td>250.24*</td>
<td>248.78*</td>
</tr>
<tr>
<td>B5 SME</td>
<td>54.99</td>
<td>2447.00</td>
<td>290.20</td>
<td>945.50</td>
<td>254.55</td>
<td>245.70</td>
</tr>
<tr>
<td>B20 SME</td>
<td>56.46</td>
<td>2425.00</td>
<td>293.50</td>
<td>978.60</td>
<td>250.35</td>
<td>243.92</td>
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<tr>
<td>B50 SME</td>
<td>55.39</td>
<td>2439.00</td>
<td>292.90</td>
<td>797.90</td>
<td>267.08</td>
<td>285.88</td>
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<tr>
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<td>54.60</td>
<td>2494.00</td>
<td>288.70</td>
<td>854.00</td>
<td>280.76</td>
<td>291.54</td>
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</tbody>
</table>

* Corrected as described in SAE J 1349.
Table A.7. RME Blends comparison using the JD 4045DF150 diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFDIESEL</td>
<td>55.65*</td>
<td>2493.00</td>
<td>288.30</td>
<td>1002.00</td>
<td>250.24*</td>
<td>248.78*</td>
</tr>
<tr>
<td>B5 RME</td>
<td>55.69</td>
<td>2325.50</td>
<td>292.30</td>
<td>1003.65</td>
<td>250.33</td>
<td>273.51</td>
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<td>56.23</td>
<td>2396.00</td>
<td>294.90</td>
<td>850.60</td>
<td>250.10</td>
<td>277.64</td>
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<tr>
<td>B50 RME</td>
<td>55.27</td>
<td>2423.00</td>
<td>291.40</td>
<td>890.30</td>
<td>262.05</td>
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<td>B100 RME</td>
<td>55.78</td>
<td>2461.00</td>
<td>293.90</td>
<td>869.80</td>
<td>269.83</td>
<td>272.34</td>
</tr>
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</table>

* Corrected as described in SAE J 1349.

---

Table A.8. PME Blends comparison using the JD 4045DF150 diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak Net Brake Power, kW</th>
<th>SPEED @ Peak Power, rpm</th>
<th>Peak Torque, N-m</th>
<th>SPEED @ Peak Torque, rpm</th>
<th>BSFC @ Peak Power, g/kW-h</th>
<th>BSFC @ Peak Torque, g/kW-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFDIESEL</td>
<td>55.65*</td>
<td>2493.00</td>
<td>288.30</td>
<td>1002.00</td>
<td>250.24*</td>
<td>248.78*</td>
</tr>
<tr>
<td>B5 PME</td>
<td>55.20</td>
<td>2418.00</td>
<td>287.10</td>
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<td>266.61</td>
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<td>54.79</td>
<td>2465.00</td>
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<td>868.50</td>
<td>273.13</td>
<td>296.34</td>
</tr>
</tbody>
</table>

* Corrected as described in SAE J 1349.
### Table A.9. SFME Blends comparison on exhaust emissions of Yanmar 3009D diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>NOx, ppm</th>
<th>SO2, ppm</th>
<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF-DIESEL</td>
<td>304.43</td>
<td>0.00</td>
<td>177.39</td>
<td>6.90</td>
<td>26.23</td>
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<tr>
<td>B5 SFME</td>
<td>307.54</td>
<td>0.00</td>
<td>147.23</td>
<td>7.04</td>
<td>34.46</td>
</tr>
<tr>
<td>B20 SFME</td>
<td>404.52</td>
<td>0.00</td>
<td>117.48</td>
<td>8.13</td>
<td>41.71</td>
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<tr>
<td>B100 SFME</td>
<td>408.83</td>
<td>0.00</td>
<td>142.36</td>
<td>7.86</td>
<td>31.45</td>
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</tbody>
</table>

### Table A.10. PME Blends comparison on exhaust emissions of Yanmar 3009D diesel engine.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>NOx, ppm</th>
<th>SO2, ppm</th>
<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF-DIESEL</td>
<td>231.16</td>
<td>10.77</td>
<td>153.81</td>
<td>7.12</td>
<td>10.77</td>
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<tr>
<td>B5 PME</td>
<td>221.90</td>
<td>7.00</td>
<td>132.00</td>
<td>7.18</td>
<td>8.48</td>
</tr>
<tr>
<td>B20 PME</td>
<td>235.32</td>
<td>4.35</td>
<td>141.84</td>
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<td>14.90</td>
</tr>
<tr>
<td>B20 PME</td>
<td>255.81</td>
<td>7.10</td>
<td>108.74</td>
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<td>9.90</td>
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<td>B100 PME</td>
<td>300.72</td>
<td>6.21</td>
<td>121.24</td>
<td>8.38</td>
<td>14.03</td>
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### Table A.11. CFME Blends comparison on exhaust emissions using JD 4045DF150 diesel engine.

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<th>Fuel</th>
<th>NOx, ppm</th>
<th>SO2, ppm</th>
<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF-DIESEL</td>
<td>441</td>
<td>0</td>
<td>138</td>
<td>6.4</td>
<td>15</td>
</tr>
<tr>
<td>B5 CFME</td>
<td>416</td>
<td>7</td>
<td>136</td>
<td>7</td>
<td>26</td>
</tr>
<tr>
<td>B20 CFME</td>
<td>431</td>
<td>3</td>
<td>119</td>
<td>7.5</td>
<td>23</td>
</tr>
<tr>
<td>B50 CFME</td>
<td>452</td>
<td>3</td>
<td>105</td>
<td>7.7</td>
<td>21</td>
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<td>B100 CFME</td>
<td>493</td>
<td>0</td>
<td>86</td>
<td>7</td>
<td>13</td>
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### Table A.12. SME Blends comparison on exhaust emissions using JD 4045DF150 diesel engine.

<table>
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<th>Fuel</th>
<th>NOx, ppm</th>
<th>SO2, ppm</th>
<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF Diesel</td>
<td>441</td>
<td>0</td>
<td>138</td>
<td>6.4</td>
<td>15</td>
</tr>
<tr>
<td>B5 SME</td>
<td>461</td>
<td>0</td>
<td>136</td>
<td>7.6</td>
<td>20</td>
</tr>
<tr>
<td>B20 SME</td>
<td>437</td>
<td>0</td>
<td>100</td>
<td>7</td>
<td>15</td>
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<tr>
<td>B50 SME</td>
<td>514</td>
<td>0</td>
<td>80</td>
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<td>26</td>
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<td>522</td>
<td>0</td>
<td>55</td>
<td>6.3</td>
<td>22</td>
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</table>

### Table A.13. RME Blends comparison on exhaust emissions using JD 4045DF150 diesel engine.

<table>
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<th>Fuel</th>
<th>NOx, ppm</th>
<th>SO2, ppm</th>
<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF Diesel</td>
<td>454</td>
<td>0</td>
<td>138</td>
<td>6.4</td>
<td>15</td>
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<tr>
<td>B5 RME</td>
<td>350</td>
<td>3</td>
<td>147.5</td>
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<tr>
<td>B20 RME</td>
<td>526</td>
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<td>168.67</td>
<td>8.2</td>
<td>18.67</td>
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<tr>
<td>B50 RME</td>
<td>482</td>
<td>3</td>
<td>109</td>
<td>8.2</td>
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<tr>
<td>B100 RME</td>
<td>627</td>
<td>0</td>
<td>76</td>
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</table>

### Table A.14. PME Blends comparison on exhaust emissions using JD 4045DF150 diesel engine.

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<th>CO, ppm</th>
<th>CO2, %</th>
<th>THC, ppm</th>
</tr>
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<tr>
<td>REF Diesel</td>
<td>441</td>
<td>0</td>
<td>138</td>
<td>6.4</td>
<td>15</td>
</tr>
<tr>
<td>B5 PME</td>
<td>486</td>
<td>7</td>
<td>142</td>
<td>8</td>
<td>23</td>
</tr>
<tr>
<td>B20 PME</td>
<td>471</td>
<td>0</td>
<td>131</td>
<td>7.5</td>
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<tr>
<td>B50 PME</td>
<td>465</td>
<td>3</td>
<td>98</td>
<td>6.7</td>
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<tr>
<td>B100 PME</td>
<td>521</td>
<td>0</td>
<td>109</td>
<td>6.2</td>
<td>9</td>
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</tbody>
</table>
Figure B.1. Relationship between soybean oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the Yanmar engine.
Figure B.2. Relationship between canola oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the Yanmar engine.
Figure B.3. Relationship between sunflower oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the Yanmar engine.
Figure B.4. Relationship between peanut oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the Yanmar engine.
Figure B.5. Relationship between soybean oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the JD 4045DF150 engine.
Figure B.6. Relationship between canola oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the JD 4045DF150 engine.
Figure B.7. Relationship between peanut oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the JD 4045DF150 engine.
Figure B.8. Relationship between chicken fat oil biodiesel and its blends with standard no. 2 petroleum diesel with some engine performance parameters. Data obtained from the JD 4045DF150 engine.
Figure B.9. Relationship between peanut oil biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the Yanmar engine.
Figure B.10. Relationship between sunflower oil biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the Yanmar engine.
Figure B.11. Relationship between soybean oil biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the JD 4045DF150 engine.
Figure B.12. Relationship between canola oil biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the JD 4045DF150 engine.
Figure B.12. Relationship between peanut oil biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the JD 4045DF150 engine.
Figure B.13. Relationship between chicken fat biodiesel and its blends with standard no. 2 petroleum diesel with some of the EPA regulated exhaust emission concentrations. Data obtained from the JD 4045DF150 engine.
APPENDIX C

Table C.1. Randomized complete block experimental design used for each feedstock in each engine.

<table>
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<tr>
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<td>SO2, ppm</td>
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</table>
APPENDIX D

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Tel: +44 (0)1344 636300  Fax: +44 (0)1344 291194  E-mail: standards@saiglobal.com

Web: www.ili.co.uk
Standard Specification for
Biodiesel Fuel Blend Stock (B100) for Middle Distillate
Fuels

This standard is issued under the fixed designation D 6751; the number immediately following the designation indicates the year of
original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A
superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers biodiesel (B100) Grades S15
and S500 for use as a blend component with middle distillate
fuels.

1.2 This specification prescribes the required properties
of diesel fuels at the time and place of delivery. The specification
requirements may be applied at other points in the production
and distribution system when provided by agreement between
the purchaser and the supplier.

1.3 Nothing in this specification shall preclude observance
of federal, state, or local regulations which may be more
restrictive.

Note 1—The generation and dissipation of static electricity
may create problems in the handling of distillate fuel oils
with which biodiesel may be blended. For more information
on the subject, see Guide D 4865.

1.4 The values stated in SI units are to be regarded as
standard. No other units of measurement are included in this
standard.

1.4.1 Exception—In Annex A1, the values stated in SI units
are to be regarded as the standard. The values given in
parentheses are for information only.

2. Referenced Documents

2.1 ASTM Standards:

D 93 Test Method for Flash Point by Pensky-Marten
Closed Cup Tester
D 130 Test Method for Corrosiveness to Copper from
Petroleum Products by Copper Strip Test
D 189 Test Method for Corrosion Carbon Residue of
Petroleum Products

D 445 Test Method for Kinematic Viscosity of Transparent
and Opaque Liquids (and Calculation of Dynamic Viscosity)
D 524 Test Method for Rumbottom Carbon Residue of
Petroleum Products
D 613 Test Method for Cetane Number of Diesel Fuel Oil
D 664 Test Method for Acid Number of Petroleum Products
by Potentiometric Titration
D 874 Test Method for Sulfated Ash from Lubricating Oils
and Additives
D 974 Test Method for Acid and Base Number by Color-
Indicator Titration
D 975 Specification for Diesel Fuel Oils
D 976 Test Method for Calculated Cetane Index of Distillate
Fuels
D 1160 Test Method for Distillation of Petroleum Products
at Reduced Pressure
D 1266 Test Method for Sulfur in Petroleum Products
Lamp Method
D 1796 Test Method for Water and Sediment in Fuel Oils by
the Centrifuge Method (Laboratory Procedure)
D 2274 Test Method for Oxidation Stability of Distillate
Fuel Oil (Accelerated Method)
D 2500 Test Method for Cloud Point of Petroleum Products
D 2622 Test Method for Sulfur in Petroleum Products by
Wavelength Dispersive X-ray Fluorescence Spectroscopy
t
D 2709 Test Method for Water and Sediment in Middle
Distillate Fuels by Centrifuge
D 2880 Specification for Gas Turbine Fuel Oils
D 3117 Test Method for Wax Appearance Point of Distillate
Fuels
D 3120 Test Method for Trace Quantities of Sulfur in Light
Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry
D 3242 Test Method for Acidity in Aviation Turbine Fuel
D 3828 Test Methods for Flash Point by Small Scale Closed
Cup Tester
D 4057 Practice for Manual Sampling of Petroleum and
Petroleum Products
D 4177 Practice for Automatic Sampling of Petroleum and
Petroleum Products

1 This specification is under the jurisdiction of ASTM Committee D02 on
Petroleum Products and Lubricants and is the direct responsibility of Subcommittee
D02.02 on Burner, Diesel, Non-Airplane Gas Turbine, and Marine Fuels.
approved in 1999 as PS 121-99. Adopted as a standard in 2002 as D 6751-02. Last
previous edition approved in 2007 as D 6751-07.7
2 For referenced ASTM standards, visit the ASTM website, www.astm.org, or
contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM
Standards volume information, refer to the standard’s Document Summary page on
the ASTM website.

A Summary of Changes section appears at the end of this standard.

Copyright © ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.
D 4294 Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectrometry

D 4530 Test Method for Determination of Carbon Residue (Micro Method)

D 4737 Test Method for Calculated Cetane Index by Four Variable Equation

D 4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems

D 4951 Test Method for Determination of Additive Elements in Lubricating Oils by Inductively Coupled Plasma Atomic Emission Spectrometry

D 5452 Test Method for Particulate Contamination in Aviation Fuels by Laboratory Filtration

D 5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence

D 5773 Test Method for Cloud Point of Petroleum Products (Constant Cooling Rate Method)

D 6217 Test Method for Particulate Contamination in Middle Distillate Fuels by Laboratory Filtration

D 6300 Practice for Determination of Precision and Bias Data for Use in Test Methods for Petroleum Products and Lubricants

D 6450 Test Method for Flash Point by Continuously Closed Cup (CCCP) Tester

D 6469 Guide for Microbial Contamination in Fuels and Fuel Systems

D 6584 Test Method for Determination of Free and Total Glycerin in B-100 Biodiesel Methyl Esters By Gas Chromatography

D 6890 Test Method for Determination of Ignition Delay and Derived Cetane Number (DCN) of Diesel Fuel Oils by Combustion in a Constant Volume Chamber

D 7039 Test Method for Sulfur in Gasoline and Diesel Fuel by Monochromatic Wavelength Dispersive X-ray Fluorescence Spectrometry

2.2 Government Standard:

40 CFR Part 79 Registration of Fuels and Fuel Additives Section 211(b) Clean Air Act

2.3 Other Documents:

UOP 389 Trace Metals in Oils by Wet Ashing and ICP-OES

UOP 391-91 Trace Metals in Petroleum Products or Organics by AAS

EN 14112 Fat and oil derivatives—Fatty acid methyl esters (FAME)—Determination of oxidation stability (Accelerated oxidation test)\(^5\)

EN 14110 Fat and oil derivatives—Fatty acid methyl esters (FAME)—Determination of methanol content\(^6\)

EN 14538 Fat and oil derivatives—Fatty acid methyl esters (FAME)—Determination of Cu, K, Mg and Na content by optical emission spectral analysis with inductively coupled plasma (ICP OES)\(^3\)

3. Terminology

3.1 Definitions:

3.1.1 biodiesel, \(n\)—fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100.

3.1.1.1 Discussion—biodiesel, as defined above, is registered with the U.S. EPA as a fuel and a fuel additive under Section 211(b) of the Clean Air Act. There is, however, other usage of the term biodiesel in the marketplace. Due to its EPA registration and the widespread commercial use of the term biodiesel in the U.S. marketplace, the term biodiesel will be maintained for this specification.

3.1.1.2 Discussion—Biodiesel is typically produced by a reaction of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the presence of a catalyst to yield mono-alkyl esters and glycerin, which is removed. The finished biodiesel derives approximately 10% of its mass from the reacted alcohol. The alcohol used in the reaction may or may not come from renewable resources.

3.1.2 biodiesel blend (BXX), \(n\)—blend of biodiesel fuel with diesel fuel oils.

3.1.2.1 Discussion—In the abbreviation BXX, the XX represents the volume percentage of biodiesel fuel in the blend.

3.1.3 biodiesel fuel, \(n\)—synonym for biodiesel.

3.1.4 diesel fuel, \(n\)—middle petroleum distillate fuel.

3.1.5 free glycerin, \(n\)—a measure of the amount of glycerin remaining in the fuel.

3.1.6 Grade S15 B100, \(n\)—a grade of biodiesel meeting ASTM Specification D 6751 and having a sulfur specification of 15 ppm maximum.

3.1.7 Grade S500 B100, \(n\)—a grade of biodiesel meeting ASTM Specification D 6751 and having a sulfur specification of 500 ppm maximum.

3.1.8 middle distillate fuel, \(n\)—kerosines and gas oils boiling between approximately 150°C and 400°C at normal atmospheric pressure and having a closed-cup flash point above 35°C.

3.1.9 total glycerin, \(n\)—the sum of the free glycerin and the glycerin portion of any unreacted or partially reacted oil or fat.

4. Requirements

4.1 The biodiesel specified shall be mono-alkyl esters of long chain fatty acids derived from vegetable oils and animal fats.

4.2 Unless otherwise specified, samples for analysis shall be taken by the procedure described in Practices D 4057 or D 4177.

4.3 The biodiesel specified shall conform to the detailed requirements shown in Table 1.

Note 2—A considerable amount of experience exists in the U.S. with a 20% blend of biodiesel, primarily produced from soybean oil, with 80% diesel fuel (B20). Experience with biodiesel produced from animal fat and other oils is similar. Experience with B20 and lower blends in other applications is not as prevalent. Although biodiesel (B100) can be used, blends of over 20% biodiesel with diesel fuel (B20) should be evaluated on a case by case basis until further experience is available.

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\(^{b}\) Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA. Visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

\(^{c}\) Available from the National CEN Members listed on the CEN website (www.cenorm.be) or from the CEN/TC19 secretariat (astm@cen.nl).
TABLE 1 Detailed Requirements for Biodiesel (B100) (All Sulfur Levels)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method*</th>
<th>Grade</th>
<th>Grade</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S15</td>
<td>S500</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limits</td>
<td>Limits</td>
<td></td>
</tr>
<tr>
<td>Calcium and Magnesium, combined</td>
<td>EN 14550</td>
<td>5 max</td>
<td>5 max</td>
<td>ppm (µg/g)</td>
</tr>
<tr>
<td>Alcohol control</td>
<td>EN 14110</td>
<td>0.2 max</td>
<td>0.2 max</td>
<td>mass %</td>
</tr>
<tr>
<td>Flash point (closed cup)</td>
<td>D 93</td>
<td>90 min</td>
<td>90 min</td>
<td>°C</td>
</tr>
<tr>
<td>One of the following must be met:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Method control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Flash point</td>
<td>D 93</td>
<td>150 min</td>
<td>150 min</td>
<td>°C</td>
</tr>
<tr>
<td>Water and sediment</td>
<td>D 2709</td>
<td>0.059 max</td>
<td>0.059 max</td>
<td>% volume</td>
</tr>
<tr>
<td>Kinematic viscosity, 40°C</td>
<td>D 445</td>
<td>1.5-4.0P</td>
<td>1.5-4.0P</td>
<td>mass %</td>
</tr>
<tr>
<td>Sulfated ash</td>
<td>D 874</td>
<td>0.020 max</td>
<td>0.020 max</td>
<td>mass %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>D 6450</td>
<td>0.0019 max (10)</td>
<td>0.006 max (600)</td>
<td>mass (ppm)</td>
</tr>
<tr>
<td>Copper strip corrosion</td>
<td>D 130</td>
<td>No. 3 max</td>
<td>No. 3 max</td>
<td></td>
</tr>
<tr>
<td>Gelatin number</td>
<td>D 613</td>
<td>47 min</td>
<td>47 min</td>
<td></td>
</tr>
<tr>
<td>Cloud point</td>
<td>D 2500</td>
<td>Reportb</td>
<td>Reportb</td>
<td>°C</td>
</tr>
<tr>
<td>Carbon residue</td>
<td>D 4560</td>
<td>0.059 max</td>
<td>0.059 max</td>
<td></td>
</tr>
<tr>
<td>Acid number</td>
<td>D 694</td>
<td>0.50 max</td>
<td>0.50 max</td>
<td>mg KOH/g</td>
</tr>
<tr>
<td>Cold soak filterability</td>
<td>Annex A1</td>
<td>360 maxc</td>
<td>360 maxc</td>
<td>seconds</td>
</tr>
<tr>
<td>Free glycerin</td>
<td>D 6934</td>
<td>0.029 max</td>
<td>0.029 max</td>
<td></td>
</tr>
<tr>
<td>Total glycerol</td>
<td>D 6935</td>
<td>0.249 max</td>
<td>0.249 max</td>
<td></td>
</tr>
<tr>
<td>Phosphorus content</td>
<td>D 4951</td>
<td>0.001 max</td>
<td>0.001 max</td>
<td></td>
</tr>
<tr>
<td>Distillation temperature, atmospheric</td>
<td>D 1110</td>
<td>360 max</td>
<td>360 max</td>
<td>°C</td>
</tr>
<tr>
<td>equivalent/equivalent temperature, 98 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>recovered</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium and Potassium, combined</td>
<td>EN 14550</td>
<td>5 max</td>
<td>5 max</td>
<td>ppm (µg/g)</td>
</tr>
<tr>
<td>Oxidation stability</td>
<td>EN 14115</td>
<td>3 minimum</td>
<td>3 minimum</td>
<td>hours</td>
</tr>
</tbody>
</table>

* The test methods indicated are the approved referee methods. Other acceptable methods are indicated in 5.1.

b Other sulfur limits can apply in selected areas in the United States and in other countries.

b The cloud point of biodiesel is generally higher than petroleum based diesel fuel and should be taken into consideration when blending.

b Carbon residue shall be run on the 100 % sample (see 5.1.11).

b B100 intended for blending into diesel fuel that is expected to give satisfactory vehicle performance at fuel temperatures at or below −12°C shall comply with a cold soak filterability limit of 200 s maximum.

Norm 3—The user should consult the equipment manufacturer or owner’s manual regarding the suitability of using biodiesel or biodiesel blends in a particular engine or application.

5. Test Methods

5.1 The requirements enumerated in this specification shall be determined in accordance with the following methods.

5.1.1 Flash Point—Test Methods D 93, except where other methods are prescribed by law. Test Methods D 3828 or D 6450 can also be used. The precision and bias of Test Methods D 3828 and D 6450 with biodiesel is not known and is currently under investigation. Test Methods D 93 shall be the referee method.

5.1.2 Water and Sediment—Test Method D 2709. Test Method D 1796 may also be used. Test Method D 2709 shall be the referee method. The precision and bias of these test methods with biodiesel is not known and is currently under investigation.

5.1.3 Viscosity—Test Method D 445.

5.1.4 Sulfated Ash—Test Method D 874.

5.1.5 Oxidation Stability—Test Method EN 14112.

5.1.6 Sulfur—Test Method D 5453. Test Method D 7039 may also be used. Other test methods may also be suitable for determining up to 0.05 % (500 ppm) sulfur in biodiesel fuels such as Test Methods D 1266, D 2622, D 3120 and D 4294 but may provide falsely high results (see X1.5) although their precision and bias with biodiesel is unknown. Test Method D 5453 shall be the referee test method.

5.1.7 Corrosion—Test Method D 130, 3 h test at 50°C.

5.1.8 Cold Filter Plugging Point—Test Method D 6890 may also be used. Test Method D 613 shall be the referee method.

5.1.9 Cloud Point—Test Method D 2500. Test Method D 5773 may also be used. Test Method D 3117 may also be used because it is closely related. Test Method D 2500 shall be the referee test method. The precision and bias of Test Method D 3117 for biodiesel is not known and is currently under investigation.

5.1.10 Acid Number—Test Method D 664. Test Methods D 3242 or D 974 may also be used. Test Method D 664 shall be the referee test method.

5.1.11 Carbon Residue—Test Method D 4530. A 100 % sample shall replace the 10 % residual, with percent residue in the original sample reported using the 10 % residual calculation (see X1.9.1). Test Methods D 189 or D 524 may also be used. Test Method D 4530 shall be the referee method.

5.1.12 Total Glycerin—Test Method D 6584.

5.1.13 Free Glycerin—Test Method D 6584.

5.1.14 Phosphorus Content—Test Method D 4951.

5.1.15 Distillation Temperature, Reduced Pressure—Test Method D 1160.

5.1.16 Calcium and Magnesium, combined—Test Method EN 14538. Test Method UOP 389 may also be used. Test Method EN 14538 shall be the referee test method.

5.1.17 Sodium and Potassium, combined—Test Method EN 14538. Test Method UOP 391 may also be used. Test Method EN 14538 shall be the referee test method.

5.1.18 Cold Soak Filterability—The test method in Annex A1 shall be used to determine the cold soak filterability. B100 intended for blending into diesel fuels that is expected to give satisfactory vehicle performance at fuel temperatures at or below −12°C shall comply with a cold soak filtration limit of
200 s maximum. A cold soak filterability standard test method is under development.

Note 4—Interim precision information is provided in Annex A1 for the cold soak filterability test to give the user some indication of the repeatability and reproducibility expected.

6. Workmanship

6.1 The biodiesel fuel shall be visually free of undissolved water, sediment, and suspended matter.

ANNEX

(Mandatory Information)

A1. DETERMINATION OF FUEL FILTER BLOCKING POTENTIAL OF BIODIESEL (B100) BLEND STOCK BY COLD SOAK LABORATORY FILTRATION

A1.1 Scope

A1.1.1 This test method covers the determination by filtration time after cold soak of the suitability for a Biodiesel (B100) Blend Stock for blending with middle distillates to provide adequate low temperature operability performance to at least the cloud point of the finished blend.

A1.1.2 The interim precision of this test method has been determined.

A1.1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

A1.1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

A1.2 Referenced Documents

A1.2.1 ASTM Standards: 2

A1.2.1.1 D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products

A1.2.1.2 D 4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems

A1.2.1.3 D 5452 Test Method for Particulate Contamination in Aviation Fuels by Laboratory Filtration

A1.3 Terminology

A1.3.1 Definitions:

A1.3.1.1 biodiesel, n—fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100.

A1.3.1.2 bond, v—to connect two parts of a system electrically by means of a conductive wire to eliminate voltage differences.

A1.3.1.3 ground, v—to connect electrically with earth.

A1.3.2 Definitions of Terms Specific to This Standard:

A1.3.2.1 filtered flashing fluids, n—either of two solvents, heptane or 2,2,4-trimethylpentane, filtered through a nominal 0.45 μm glass fiber filter.

A1.3.2.2 glass fiber filter, n—the 0.7 μm glass fiber filters used in this test method.

A1.3.3 Abbreviations:

A1.3.3.1 CSFT—cold soak filtration test.

A1.4 Summary of Test Method

A1.4.1 In this test method, 300 mL of biodiesel (B100) is stored at 4.4°C (40°F) for 16 h, allowed to warm to 20 to 22°C (68 to 72°F), and vacuum filtered through a single 0.7 μm glass fiber filter.

A1.4.2 In this test method, the filtration time is reported in seconds.

A1.5 Significance and Use

A1.5.1 Some substances that are soluble or appear to be soluble in biodiesel at room temperature will, upon cooling or standing at room temperature for extended periods, come out of solution. These substances can cause filter plugging. This test method provides an accelerated means of assessing the propensity for these substances to plug filters.

A1.5.1.1 Fuels that give short filtration times are expected to give satisfactory operation down to the cloud point of biodiesel blends.

A1.5.2 The test method can be used in specifications as a means of controlling levels of minor filter plugging components in biodiesel and biodiesel blends.

A1.6 Apparatus

A1.6.1 Filtration System—Arrange the following components as shown in Fig. A1.1.

A1.6.1.1 Funnel and Funnel Base, with a stainless steel filter support for a 47-mm diameter glass fiber filter and a locking ring or spring action clip capable of receiving 300 mL.

Note A1.1—Sintered glass supports were found to give much higher filtration times during initial studies and should not be used.

A1.6.1.2 Ground/Bond Wire, 0.912 to 2.59 mm (No. 10 through No. 19) bare-stranded flexible stainless steel or copper installed in the flasks and grounded as shown in Fig. A1.1.

Note A1.2—The electrical bonding apparatus described in Test
Method D 5452 or other suitable means of electrical grounding which ensure safe operation of the filtration apparatus and flask can be used. If the filtrate is to be subsequently tested for stability it is advisable not to use copper as copper ions catalyze gum formation during the stability test.

A1.6.1.3 Receiving Flask, 1-L borosilicate glass vacuum filter flask, into which the filtration apparatus fits, equipped with a sidearm to connect to the safety flask.

A1.6.1.4 Safety Flask, 1-L borosilicate glass vacuum filter flask equipped with a sidearm to connect the vacuum system. A fuel and solvent resistant rubber hose, through which the grounding wire passes, shall connect the sidearm of the receiving flask to the tube passing through the rubber stopper in the top of the safety flask.

A1.6.1.5 Vacuum System, a vacuum system capable of producing a vacuum of 70 to 100 kPa below atmospheric pressure when measured at the receiving flask. A mechanical vacuum pump may be used if it has this capability.

Note: A1.3—Water aspirated vacuum will not provide relative vacuum within the prescribed range.

A1.6.2 Other Apparatus:

A1.6.2.1 Forceps, approximately 12-cm long, flat-bladed, with non-serrated, non-pointed tips.

A1.6.2.2 Graduated Cylinders, to contain at least 0.5 L of fluid and marked at 10-ml intervals. Graduated cylinders, 100-ml, may be required for samples which filter slowly.

A1.6.2.3 Petri Dishes, approximately 12.5 cm in diameter, with removable glass supports for glass fiber filters.

Note: A1.4—Small watch glasses, approximately 5 to 7 cm in diameter, have also been found suitable to support the glass fiber filters.

Note A1.5—B100 will dissolve some plastics. This can cause the filters to adhere to the plastic.

A1.6.2.4 Glass Fiber Filters, plain, 47-mm diameter, nominal pore size 0.7-μm.

A1.6.2.5 Protective Cover, polyethylene film or clean aluminum foil.

A1.6.2.6 Liquid or Air Bath or Chamber, capable of sustaining a temperature of $4.4 \pm 1.1^\circ C$ ($40 \pm 2^\circ F$) for 16 h.

A1.6.2.7 Timer, capable of displaying elapsed times of at least 900 s to the nearest 0.1 s.

A1.7 Reagents and Materials

A1.7.1 Purity of Reagents—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available. Other grades may be used, provided it is first ascertained that the reagent is of sufficient purity to permit its use without lessening the accuracy of the determination.

A1.7.2 Flushing Fluids—Flushing fluids are not required for the test as the filter is not weighed. However, heptane or isooctane may be used to wash the apparatus after filtration to remove any residue. Alternatively soap and water may be used in accordance with A1.7.3.

A1.7.2.1 Heptane, (Warning—Flammable).
A1.7.2.2 2,2,4-trimethylpentane (isooctane), (Warning—Flammable).
A1.7.3 Liquid or Powder Detergent, water-soluble, for cleaning glassware.

A1.8 Preparation of Apparatus and Sample Containers
A1.8.1 Clean all components of the filtration apparatus using the reagents described in A1.7.2 and A1.7.3.
A1.8.1.1 Remove any labels, tags, and so forth.

A1.9 Sampling
A1.9.1 The sample container should be 500 ± 15 mL in volume and have a screw-on cap with an inert liner. Glass containers are preferred to facilitate a visual inspection of the contents and the container before and after filling. Glass containers also allow for visual inspection of the container, after the sample is emptied, to confirm complete emptying of the container. Epoxy-lined sample cans, polytetrafluoroethylene (PTFE) bottles, and high density linear polyethylene bottles have also been found suitable as sample containers but are less desirable since visual inspection of the interior of the container is more difficult.
A1.9.2 Precautions to avoid sample contamination shall include selection of an appropriate sampling point. It is preferred to obtain samples dynamically from a sampling loop in a distribution line, or from the flushing line of a field sampling kit. Ensure that the line to be sampled is flushed with fuel before collecting the sample.
A1.9.2.1 Use clean sample containers.
A1.9.2.2 Keep a clean protective cover over the top of the sample container until the cap is installed. Similarly protect the funnel opening of the assembled filtration apparatus with a clean protective cover until ready for use.
A1.9.2.3 Where it is desirable or only possible to obtain samples from static storage, follow the procedures given in Practice D 4057 or equivalent, taking precautions for cleanliness of all equipment used. The sample should pass through a minimum number of intermediate containers prior to placement in the prepared container.
A1.9.2.4 Samples obtained from static storage can give results that are not representative of the bulk contents of the tank because of particulate matter settling. Where possible, the contents of the tank should be circulated or agitated before sampling, or the sampling should be performed shortly after a tank has been filled.
A1.9.3 Visually inspect the sample container before taking the samples to verify that there are no visible particles present inside the container. Fill the sample container to contain 300 mL. Protect the fuel sample from prolonged exposure to light by wrapping the container in aluminum foil or storing it in the dark to reduce the possibility of particulate formation by light-promoted reactions. Do not transfer the fuel sample from its original sample container into an intermediate storage container. If the original sample container is damaged or leaking, then a new sample shall be obtained.
A1.9.3.1 If a 500-mL bottle is not available, or the sample has already been received in a container not suitable for this test, follow A1.9.5.

A1.9.4 Analyze fuel samples as soon as possible after sampling.
A1.9.4.1 Upon receipt of a Biodiesel Blend Stock (B100) sample, the entire sample shall be heated to 40°C for at least 3 h under an inert atmosphere to erase any thermal history and to dissolve any solids that might have precipitated during transit unless it is known that the sample has never been cooled below 20°C. If the sample has never been exposed to temperatures below 20°C then proceed to A1.9.5.
A1.9.4.2 After heating for the required time, allow the sample to sit for 24 h at a temperature no lower than 20°C.
A1.9.5 Shake the sample vigorously for 1 min, and transfer 300 mL to a clean fresh 500 ± 15 mL bottle.

A1.10 Preparation of Glass Fiber Filter
A1.10.1 Each filtration uses one filter. The glass fiber filter used for each individual test shall be identified by marking the petri dishes used to hold and transport the filters.
A1.10.2 Clean all glassware used in preparation of glass fiber filter as described in A1.8.1.
A1.10.3 Using forceps, place the filters on clean glass support rods or watch glasses in petri dish.
A1.10.4 Place the petri dish with its lid slightly ajar in a drying oven at 90 ± 5°C, and leave it for 30 min.
A1.10.5 Remove the petri dish from the drying oven. Keep the petri dish cover ajar, such that the filter is protected from contamination from the atmosphere. Allow 30 min for the filter to come to equilibrium with room air temperature and humidity.
A1.10.6 Using clean forceps, place the filter centrally on the filter support of the filtration apparatus (see Fig. A1.1). Install the funnel and secure with locking ring or spring clip. Do not remove the plastic film from the funnel opening until ready to start filtration.

A1.11 Procedure
A1.11.1 Place 300 mL of sample in a glass 500–mL bottle, and set in a liquid or air bath or chamber at 4.4 ± 1.1°C (40 ± 2°F) for 16 ± 0.5 h.
A1.11.2 After the 16-h cold soak is completed, allow the sample to come back to room temperature at 20 to 22°C (68 to 72°F) on its own without external heating. The sample shall be completely liquid before filtration. The sample shall be filtered within 1 h after reaching 20 to 22°C (68 to 72°F).
A1.11.3 Complete assembly of the receiving flask, 0.7 μm glass fiber filter and funnel as a unit (see Fig. A1.1) before swirling the sample. To minimize operator exposure to fumes, the filtering procedure should be performed in a fume hood.
A1.11.4 Start the vacuum system. Record the pressure in the system after 1 min of filtration. The vacuum shall be between 71.1 and 84.7 kPa (21 and 25 in. Hg) below atmospheric pressure. If the vacuum is not within the specified range, make adjustments to the vacuum system.
A1.11.5 Thoroughly clean the outside of the sample container in the region of the cap by wiping it with a damp, lint-free cloth. Swirl the container vigorously for about 2 to 3 s to dislodge any particles that may have adhered to the walls of the container.
A1.11.6 Immediately after swirling, pour the entire contents of the sample container into the filtration funnel and simultaneously start the timer. The entire contents of the sample container shall be filtered through the glass fiber filter to ensure a correct measure of the contamination in the sample.

Note: A1.6—Take care not to shake the sample vigorously, as this could cause some of the solids to go back into solution.

A1.11.7 If the filtration is not complete when 720 s (12 min) has elapsed, turn off the vacuum system and record the duration of the filtration to the nearest second. Record the pressure in the system and the volume filtered just before the termination of the filtration.

A1.12 Reporting

A1.12.1 Report the time for the 300-mL B100 to be completely filtered as B100 filtration time in seconds.

A1.12.2 If the filtration of the 300 mL failed to be completed after 720 s, report the volume that was filtered after 720 s.

A1.13 Precision and Bias

A1.13.1 Precision—The precision of this test method for B100 filtration has not yet been determined.

A1.13.1.1 Repeatability—The difference between successive test results, obtained by the same operator using the same apparatus under constant operating conditions on identical test material for B100 filtration has not yet been determined.

A1.13.1.2 Reproducibility—The difference between the two single and independent results obtained by different operators working in different laboratories on identical test material for B100 filtration has not yet been determined.

A1.13.1.3 Interim Precision—Repeatability and reproducibility determinations were made using data from the ASTM Biodiesel Low Temperature Operability Task Force. The analysis of the data is the subject of a research report, RR:D02:1649.7 The report is an attempt to supply such an analysis based on well-established methodologies. Subsequent to test method publication a more thorough round robin is planned.

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Note: A1.7—The degree of freedom associated with the repeatability estimate from this round robin study is 25 for repeatability which is below 50 but acceptable. The degree of freedom associated with the reproducibility estimate from this round robin study is 10 and below acceptable limits. For that reason only the repeatability is included in A1.13.1.4. Since the minimum requirement of 30 (in accordance with Practice D 6300) is not met, users are cautioned that the actual repeatability/ reproducibility may be significantly different than these estimates. An ASTM ILS will be conducted in the future.

A1.13.1.4 The difference between successive test results, obtained by the same operator using the same apparatus under constant operating conditions on identical test material for B100 filtration would in the long run, in the normal and correct operation of this test method, exceed 0.1689X + 1.2018 in one case in twenty.

A1.13.2 Bias—The procedure given for the determination of B100 filtration time has no bias because the value of the filtration time is defined in terms of this test method.

A1.14 Keywords

A1.14.1 biodiesel; diesel fuel; glass fiber filter; biodiesel; filter blocking potential; cold soak filtration test, CSFT; biodiesel blend; laboratory filtration; glass fiber filter; low temperature operability; middle distillate fuel.

APPENDICES

(Nonmandatory Information)

X1. SIGNIFICANCE OF PROPERTIES SPECIFIED FOR BIODIESEL FUEL

X1.1 Introduction

X1.1.1 The properties of commercial biodiesel fuel depends upon the refining practices employed and the nature of the renewable lipids from which it is produced. Biodiesel, for example, can be produced from a variety of vegetable oils or animal fats which produce similar volatility characteristics and combustion emissions with varying cold flow properties.

X1.1.2 The significance of the properties in this appendix are based primarily on the commercial use of biodiesel in on-road and off-road diesel engine applications. Some of the properties may take on other significance if biodiesel is used as a fuel or blending component in other applications. See the respective finished product specifications for additional information on significance of properties of those applications.

X1.2 Flash Point

X1.2.1 The flash point, as specified, is not directly related to engine performance. It is, however, of importance in connection with legal requirements and safety precautions involved in fuel handling and storage that are normally specified to meet insurance and fire regulations.

X1.2.2 The flash point for biodiesel has been set at 93°C (200°F) minimum, so biodiesel falls under the non-hazardous category under National Fire Protection Association codes.

X1.3 Viscosity

X1.3.1 For some engines it may be advantageous to specify a minimum viscosity because of power loss due to injection pump and injector leakage. Maximum allowable viscosity, on
the other hand, is limited by considerations involved in engine design and size, and the characteristics of the injection system.

The upper limit for the viscosity of biodiesel (6.0 mm²/s at 40°C) is higher than the maximum allowable viscosity in Specification D 975 Grade 2-D and 2-D low sulfur (4.1 mm²/s at 40°C). Blending biodiesel with diesel fuel close to its upper limit could result in a biodiesel blend with viscosity above the upper limits contained in Specification D 975.

X1.4 Sulfated Ash

X1.4.1 Ash-forming materials may be present in biodiesel in three forms: (1) abrasive solids, (2) soluble metallic soaps, and (3) unremovable catalysts. Abrasive solids and unremovable catalysts can contribute to injector, fuel pump, piston and ring wear, and also to engine deposits. Soluble metallic soaps have little effect on wear but may contribute to filter plugging and engine deposits.

X1.5 Sulfur

X1.5.1 The effect of sulfur content on engine wear and deposits appears to vary considerably in importance and depends largely on operating conditions. Fuel sulfur can also affect emissions control systems performance and various limits on sulfur have been imposed for environmental reasons. B100 is essentially sulfur-free.

Note: X1.1—Test Method D 5453 should be used with biodiesel. Use of other test methods may provide falsely high results when analyzing B100 with extremely low sulfur levels (less than 5 ppm). Biodiesel sulfur analysis from RR: D02-1480, Biodeisel Fuel Cetane Number Testing Program, January-April, 1999, using Test Method D 2622 yielded falsely high results due to the presence of the oxygen in the biodiesel. Sulfur results using Test Method D 2622 were more accurate with B20 than with B100 due to the lower oxygen content of B20. Potential improvements to Test Method D 2622 may provide more accurate values in the future.

X1.6 Copper Strip Corrosion

X1.6.1 This test serves as a measure of possible difficulties with copper and brass or bronze parts of the fuel system. The presence of acids or sulfur-containing compounds can tarnish the copper strip, thus indicating the possibility for corrosion.

X1.7 Cetane Number

X1.7.1 Cetane number is a measure of the ignition quality of the fuel and influences white smoke and combustion roughness. The cetane number requirements depend on engine design, size, nature of speed and load variations, and on starting and atmospheric conditions.

X1.7.2 The calculated cetane index, Test Methods D 976 or D 4737, may not be used to approximate the cetane number with biodiesel or its blends. There is no substantiating data to support the calculation of cetane index with biodiesel or biodiesel blends.

X1.8 Cloud Point

X1.8.1 Cloud point is of importance in that it defines the temperature at which a cloud or haze of crystals appears in the fuel under prescribed test conditions which generally relates to the temperature at which crystals begin to precipitate from the fuel in use. Biodiesel generally has a higher cloud point than petroleum-based diesel fuel. The cloud point of biodiesel and its impact on the cold flow properties of the resulting blend should be monitored by the user to ensure trouble-free operation in cold climates. For further information, consult Appendix X4 of Specification D 975.

X1.9 Carbon Residue

X1.9.1 Carbon residue gives a measure of the carbon depositing tendencies of a fuel oil. While not directly correlating with engine deposits, this property is considered an approximation. Although biodiesel is in the distillate boiling range, most biodiesels boil at approximately the same temperature and it is difficult to leave a 10% residual upon distillation. Thus, a 100% sample is used to replace the 10% residual sample, with the calculation executed as if it were the 10% residual. Parameter E (final weight loss charge/original weight loss charge) in 8.1.2 of Test Method D 4530-93 is a constant 20/200.

X1.10 Acid Number

X1.10.1 The acid number is used to determine the level of free fatty acids or processing acids that may be present in biodiesel. Biodiesel with a high acid number has been shown to increase fueling system deposits and may increase the likelihood for corrosion.

Note: X1.2—Acid number measures a different phenomenon for biodiesel than petroleum-based diesel fuel. The acid number for biodiesel measures free fatty acids or degradation by-products not found in petroleum-based diesel fuel. Increased recycle temperatures in new fuel system designs may accelerate fuel degradation which could result in high acid values and increased filter plugging potential.

X1.11 Free Glycerin

X1.11.1 The free glycerin method is used to determine the level of glycerin in the fuel. High levels of free glycerin can cause injector deposits, as well as clogged fueling systems, and result in a buildup of free glycerin in the bottom of storage and fueling systems.

X1.12 Total Glycerin

X1.12.1 The total glycerin method is used to determine the level of glycerin in the fuel. High levels of free glycerin and the glycerine portion of any unreacted or partially reacted oil or fat. Low levels of total glycerin ensure that high conversion of the oil or fat into its mono-alkyl esters has taken place. High levels of mono-, di-, and triglycerides can cause injector deposits and may adversely affect cold weather operation and filter plugging.

X1.13 Phosphorus Content

X1.13.1 Phosphorus can damage catalytic converters used in emissions control systems and its level must be kept low. Catalytic converters are becoming more common on diesel-powered equipment as emissions standards are tightened, so low phosphorus levels will be of increasing importance. Biodiesel produced from U.S. sources has been shown to have
low phosphorus content (below 1 ppm) and the specification value of 10 ppm maximum is not problematic. Biodiesel from other sources may or may not contain higher levels of phosphorus and this specification was added to ensure that all biodiesel, regardless of the source, has low phosphorus content.

X1.14 Reduced Pressure Distillation

X1.14.1 Biodiesel exhibits a boiling point rather than a distillation curve. The fatty acids chains in the raw oils and fats from which biodiesel is produced are mainly comprised of straight chain hydrocarbons with 16 to 18 carbons that have similar boiling temperatures. The atmospheric boiling point of biodiesel generally ranges from 330 to 357°C, thus the specification value of 360°C is not problematic. This specification was incorporated as an added precaution to ensure the fuel has not been adulterated with high boiling contaminants.

Note X1.3—The density of biodiesel meeting the specifications in Table 1 falls between 0.86 and 0.90, with typical values falling between 0.88 and 0.89. Since biodiesel density falls between 0.86 and 0.90, a separate specification is not needed. The density of raw oils and fats is similar to biodiesel, therefore use of density as an expedient check of fuel quality may not be as useful for biodiesel as it is for petroleum based diesel fuel. This section has been added to provide users and engine interests with this information.

Note X1.4—In certain items of fuel injection equipment in compression ignition engines, such as rotary distributor fuel pumps and injectors, the fuel functions as a lubricant as well as a source for combustion. Blending biodiesel fuel with petroleum based compression-ignition fuel typically improves fuel lubricity.

X1.15 Alcohol Control

X1.15.1 Alcohol control is to limit the level of unreacted alcohol remaining in the finished fuel. This can be measured directly by the volume percent alcohol or indirectly through a high flash point value.

X1.15.2 The flash point specification, when used for alcohol control for biodiesel, is intended to be 100°C minimum, which has been correlated to 0.2 vol % alcohol. Typical values are over 160°C. Due to high variability with Test Method D 93 as the flash point approaches 100°C, the flash point specification has been set at 130°C minimum to ensure an actual value of 100°C minimum. Improvements and alternatives to Test Method D 93 are being investigated. Once complete, the specification of 100°C minimum may be reevaluated for alcohol control.

X1.16 Calcium and Magnesium

X1.16.1 Calcium and magnesium may be present in biodiesel as abrasive solids or soluble metallic soaps. Abrasive solids can contribute to injector, fuel pump, piston, and ring wear, as well as to engine deposits. Soluble metallic soaps have little effect on wear, but they may contribute to filter plugging and engine deposits. High levels of calcium and magnesium compounds may also be collected in exhaust particulate removal devices, are not typically removed during passive or active regeneration, and can create increased back pressure and reduced time to service maintenance.

X1.17 Sodium and Potassium

X1.17.1 Sodium and potassium may be present in biodiesel as abrasive solids or soluble metallic soaps. Abrasive solids can contribute to injector, fuel pump, piston and ring wear, and also to engine deposits. Soluble metallic soaps have little effect on wear, but they may contribute to filter plugging and engine deposits. High levels of sodium or potassium compounds may also be collected in exhaust particulate removal devices, are not typically removed during passive or active regeneration, and they can create increased back pressure and reduced period to service maintenance.

X1.18 Oxidation Stability

X1.18.1 Products of oxidation in biodiesel can take the form of various acids or polymers, which, if in high enough concentration, can cause fuel system deposits and lead to filter clogging and fuel system malfunctions. Additives designed to retard the formation of acids and polymers can significantly improve the oxidation stability performance of biodiesel. See Appendix X2 for additional information on long-term storage.

X2. LONG-TERM STORAGE OF BIODIESEL

X2.1 Scope

X2.1.1 This appendix provides guidance for consumers of biodiesel (B100) who may wish to store quantities of fuels for extended periods. Consistently successful long-term fuel storage requires attention to fuel selection, storage conditions, and monitoring of properties prior to and during storage. This appendix is directed toward biodiesel (B100) and may be more or less applicable to blends of biodiesel with petroleum based diesel fuel.

X2.1.2 Normally produced biodiesel has adequate stability properties to withstand normal storage without the formation of troublesome amounts of insoluble degradation products, although data suggests some biodiesel may degrade faster than petroleum based diesel fuel. Biodiesel that is to be stored for prolonged periods should be selected to avoid formation of sediments, high acid numbers, and high viscosities that can clog filters, affect fuel pump operation or plug combustor nozzles or injectors. The selection of biodiesel should result from supplier-user discussions.

X2.1.3 These suggested practices are general in nature and should not be considered substitutes for any requirement imposed by the warranty of the distillate fuel equipment manufacturers or by federal, state, or local government regulations. Although they cannot replace knowledge of local conditions or good engineering and scientific judgment, these suggested practices do provide guidance in developing an individual fuel management system for the biodiesel fuel user. They include suggestions in the operation and maintenance of
existing fuel storage and handling facilities and for identifying where, when, and how fuel quality should be monitored.

X2.2.2 Performance criteria for accelerated stability tests that ensure satisfactory long-term storage of biodiesel (B100) have not been established.

X2.6 Fuel Monitoring

X2.6.1 A plan for monitoring the quality of bulk fuel during prolonged storage is an integral part of a successful monitoring program. A plan to replace aged fuel with fresh product at established intervals is also desirable.

X2.6.2 Stored fuel should be periodically sampled and its quality assessed. Practice D 4057 provides guidance for sampling. Fuel contaminants and degradation products may settle to the bottom of a quiescent tank although detrimental changes to biodiesel can occur (rising acid value) without causing sediment formation. A Bottom or Clearance sample, as defined in Practice D 4057, should be included in the evaluation along with an All Level sample.

X2.6.3 The quantity of insoluble fuel contaminants present in biodiesel can be determined using Test Method D 6217 with glass fiber filters and abundant washing although no precision or bias testing has been performed with biodiesel using Test Method D 6217.

X2.6.4 The acid value of biodiesel appears to exceed its specified maximum before other deleterious fuel property changes occur. A conscientious program of measuring the acid value of biodiesel may be sufficient for monitoring biodiesel stability.

X2.7 Fuel Storage Conditions

X2.7.1 Contamination levels in fuel can be reduced by storage in tanks kept free of water, and tankage should have provisions for water draining on a scheduled basis. Water promotes corrosion, and microbiological growth may occur at a fuel-water interface. Refer to Guide D 6469 for a more complete discussion. Underground or isothermal storage is preferred to avoid temperature extremes; above-ground storage tanks should be sheltered or painted with reflective paint. High storage temperatures accelerate fuel degradation. Fixed roof tanks should be kept full to limit oxygen supply and tank breathing. The use of airtight sealed containers, such as drums or totes, can enhance the storage life of biodiesel.

X2.7.2 Copper and copper-containing alloys should be avoided with biodiesel due to increased sediment and deposit formation. Contact with lead, tin, and zinc can also cause increased sediment levels that can rapidly plug filters and should be avoided.

X2.7.3 Appendix X3 of Specification D 2880 discusses fuel contaminants as a general topic. The discussion in Specification D 2880 pertains to gas turbine combustion which may or may not be applicable to diesel engine combustion.
SUMMARY OF CHANGES

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–07b\textsuperscript{1}) that may impact the use of this standard. (Approved Oct. 1, 2008.)

2) Revised Table 1.
3) Added 5.1.18.
4) Added Note 4.

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–07a) that may impact the use of this standard. (Approved Sept. 15, 2007.)

1) Added Test Method D 6890 to Referenced Documents and 5.1.8.
2) Added Test Method D 7039 to Referenced Documents and 5.1.6.
3) Revised 1.2.

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APPENDIX E

SURFACE VEHICLE STANDARD

SAE J1349 MAR2008

Issued: 1980-12
Revised: 2006-03
Superseding: J349 AUG2004

Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating

RATIONALE

This standard is intended to provide the industry with a repeatable means of determining the as-installed net power and torque of an engine.

TABLE OF CONTENTS

1. SCOPE ........................................................................................................................................ 3
   1.1 Purpose of Standard .................................................................................................................. 3
   1.2 Field of Application .................................................................................................................. 3
   1.3 Relationship to ISO 1585 ......................................................................................................... 4

2. REFERENCES.................................................................................................................................. 4
   2.1 Applicable Publications ........................................................................................................... 4
   2.1.1 SAE Publications ................................................................................................................ 4
   2.1.2 ISO Publications ................................................................................................................. 4
   2.1.3 Federal Regulation ............................................................................................................... 5

3. TERMS AND DEFINITIONS ......................................................................................................... 5
   3.1 Net Brake Power and Torque .................................................................................................... 5
   3.2 Rated Net Power and Torque ................................................................................................... 5
   3.3 Rated Power Speed .................................................................................................................. 5
   3.4 Rated Torque Speed ................................................................................................................ 5
   3.5 Fully Equipped Engine .......................................................................................................... 5
   3.6 Reference Test Conditions ..................................................................................................... 5
   3.7 Friction Power ....................................................................................................................... 5
   3.8 Indicated Power ...................................................................................................................... 6

4. SYMBOLS, UNITS, AND SUBSCRIPTS ...................................................................................... 6
   4.1 Symbols and Units .................................................................................................................... 6
   4.2 Subscripts ............................................................................................................................... 6

5. REFERENCE TEST CONDITIONS AND CORRECTIONS ........................................................ 6
   5.1 Reference Atmospheric Conditions ....................................................................................... 7
   5.2 SI Gasoline Specifications ...................................................................................................... 7
   5.3 Reference CI Fuel Specifications ........................................................................................... 8
   5.4 Alternative Fuels .................................................................................................................... 8
   5.5 Power Correction Factor ....................................................................................................... 8

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1. SCOPE

This standard is intended to provide a method to obtain repeatable measurements that accurately reflect true engine performance in customer service. Whenever there is an opportunity for interpretation of the standard, a good faith effort shall be made to obtain the engine's typical in-service performance and avoid finding the best possible performance under the best possible conditions. Intentional biasing of engine component or assembly tolerances to optimize performance for this test is prohibited.

1.1 Purpose of Standard

This SAE Standard has been adopted by SAE to specify:

a. A basis for net engine power and torque rating

b. Reference inlet air and fuel supply test conditions

c. A method for correcting observed power and torque to reference conditions

d. A method for determining net full load engine power and torque with a dynamometer

e. A procedure to ensure that engine controls are operating in a manner consistent with customer operation.

1.2 Field of Application

This test code document is applicable to both spark ignition (SI) and compression ignition (CI) engines, naturally aspirated and pressure-charged, with and without charge air cooling. This document does not apply to aircraft or marine engines. The standard is applicable to the internal combustion engine used in a hybrid powertrain, but it does not comprehend the combined output of the hybrid powertrain.

1.2.1 This test code supersedes those portions of SAE J1349 JUN1995 dealing with net power rating. It can be used immediately, and it shall be used for testing after January 1, 2005.

1.2.2 Standard CI diesel fuel specifications are range mean values for Type 2-D EPA test fuel per Title 40, Code of Federal Regulations, Part 85-1313-2004 or most recent

1.2.3 The corresponding test code for gross power and torque rating is SAE J1995.

1.2.4 The document for mapping engine performance is SAE J1312.
1.3 Relationship to ISO 1585

ISO 1585-1992 differs from SAE J1349 in several areas, among which the most important are:

a. This document is not limited to road vehicles.

b. This document requires inlet fuel temperature be controlled to 40 °C on CI engines.

c. This document includes a reference fuel specification and requires that engine power be corrected to that specification on all CI engines.

d. This document includes a different procedure for testing engines with a laboratory charge air cooler.

e. This document stipulates a 20% duty cycle limit on variable speed cooling fans in order to qualify for testing at the minimum power loss settings.

f. This document provides procedures for transient testing of light duty vehicles with the associated changes in control parameters and exhaust back pressure

g. This document includes accessory losses if the accessories are standard on the vehicle application.

h. ISO 1585-1992 allows ±7% correction on SI and ±10% correction on CI engines.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA). www.sae.org

SAE J1312 Procedure for Mapping Engine Performance—Spark Ignition and Compression Ignition Engines


2.1.2 ISO Publications


ISO 1585 Road vehicles—Engine test code—Net power

ISO 2288 Agricultural tractors and machines—Engine test code (bench test)—Net power

ISO 3046 Reciprocating internal combustion engines—Performance

ISO 4106 Motorcycles—Engine test code—Net power

ISO 5249 Earth-moving machinery—Engine test code—Net power
2.1.3 Federal Regulation


CFR 40 Part 86.1313-2004 or most recent

3. TERMS AND DEFINITIONS

This section contains the definitions of key terms used to describe the net power and torque test.

3.1 Net Brake Power and Torque

The power and torque produced by an engine at any speed when configured as a “fully equipped” engine (per 3.5), corrected to the reference atmospheric conditions and/or reference diesel fuel specifications per Section 5, and tested in accordance to the applicable procedures contained in this standard.

3.2 Rated Net Power and Torque

The net brake power and torque produced by the engine at the rated power speed and rated torque speed, respectively.

3.3 Rated Power Speed

The engine speed at which the Rated Brake Power is achieved. The rated power speed must be achievable in the application for which the engine is rated.

3.4 Rated Torque Speed

The engine speed at which the Rated Brake Torque is achieved. The rated torque speed must be achievable in the application for which the engine is rated.

3.5 Fully Equipped Engine

A “fully equipped” engine is an engine equipped with only those accessories necessary to perform its intended service. Accessory components that are installed on all engines in the application, e.g., power steering pump, are also included on the engine for test. Table 1 in Section 8 lists the engine equipment and accessories required for the net power test.

3.6 Reference Test Conditions

The standard (reference) engine inlet air supply and inlet fuel conditions to which all power corrections are made.

3.7 Friction Power

The power required to drive the engine as equipped for the net power test. Friction power may be established by one of the following methods:

a. Preferred Method: Hot Motoring Friction—Record friction torque at wide-open throttle at each test speed run on the power test. All readings are to be taken at the same coolant and oil temperature as observed on the power test points ±3°C, and variable engine devices should be at the as calibrated settings.

b. Alternative Method: If measured friction data are not available, it is permissible to assume 85% mechanical efficiency. When measured friction data are available, they must be used in computing mechanical efficiency. When this alternative method is used, it should be noted in the reported data that the results were corrected using an assumed mechanical efficiency of 85%.
3.8 Indicated Power

Indicated power is defined as the sum of the brake power and friction power for the purpose of this document.

4. SYMBOLS, UNITS, AND SUBSCRIPTS

4.1 Symbols and Units

SI units shall be used for all measurements unless otherwise specified.

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<td>kW, hp</td>
</tr>
<tr>
<td>N</td>
<td>Engine speed</td>
<td>min⁻¹</td>
</tr>
<tr>
<td>F</td>
<td>Fuel flow</td>
<td>g/s</td>
</tr>
<tr>
<td>SG</td>
<td>Fuel density at 15 °C</td>
<td>kg/L</td>
</tr>
<tr>
<td>V</td>
<td>Fuel viscosity at 40 °C</td>
<td>mm²/s</td>
</tr>
</tbody>
</table>

* Power and torque may be expressed as HP (0.746 kW) and lb-ft (1.356 N-m). This departure from metric standards is allowed due to the common use of English units in the advertising of power and torque to consumers.

4.2 Subscripts

c = Refers to data corrected to reference inlet air and fuel supply conditions
o = Refers to data observed at the actual test conditions
d = Refers to the dry air portion of the total inlet air supply pressure
r = Refers to the reference test conditions per Section 5

5. REFERENCE TEST CONDITIONS AND CORRECTIONS

This section contains reference air and fuel supply test conditions and specifications, recommended test ranges, and applicability of the correction procedures.
5.1 Reference Atmospheric Conditions

Table 2 defines reference atmospheric conditions and test ranges for which correction factors are valid.

<table>
<thead>
<tr>
<th>TABLE 2 - REFERENCE ATMOSPHERIC CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Air Supply Pressure (absolute)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Inlet Air Supply Pressure (absolute)</td>
</tr>
<tr>
<td>Dry Air Pressure (absolute)</td>
</tr>
<tr>
<td>Inlet Air Supply Temperature</td>
</tr>
</tbody>
</table>

With the exception of humidity, no modification to the composition of intake air is permitted. Available laboratory equipment shall be set to minimize correction factors by controlling inlet air as close as possible to “reference atmospheric conditions”.

5.2 SI Gasoline Specifications

The ratings of SI engines tested under this standard must reflect the performance that a customer can obtain operating the engine on the manufacturer's recommended fuel. To achieve that, fuels used in testing must have energy content (defined as lower heating value) typical of that found in commercially available gasoline. The engine rating shall be for fuel octane values typical of commercially available fuels of the grade recommended by the manufacturer.

Maximum allowable gasoline octane numbers for engine power rating have been determined corresponding to “regular”, “mid-grade”, and “premium” fuels from surveys of pump gasoline available throughout the United States in 2007. These values are listed in Table 3. Lower heating values listed for those fuels are based on surveys of non-oxygenated pump fuels available in U.S for several years ending in 2006.

Many SI engines have electronic knock control systems that retard spark when knock is detected. If such a system is active when the engine is rated on the dynomometer, then the fuel used must be within the specified octane limits for the recommended fuel grade. An engine with a knock control system may be tested with higher octane fuel if the knock control system is disabled and the control settings are those that would be achieved when operating on customer-recommended fuel. Vehicle test procedures for determining those control settings are specified in Section 9. Engines without knock control settings may be rated on any octane level fuel provided that the control settings are those used with customer-recommended fuel.

<table>
<thead>
<tr>
<th>TABLE 3 - SI GASOLINE SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Grade</td>
</tr>
<tr>
<td>Max. Research Octane No.</td>
</tr>
<tr>
<td>Max. Motor Octane No.</td>
</tr>
<tr>
<td>Max. Pump Octane No. (R+M)/2</td>
</tr>
<tr>
<td>Max. Lower Heating Value</td>
</tr>
</tbody>
</table>
The following table shall be used in determining the fuel to be used in testing SI engines:

<table>
<thead>
<tr>
<th>Manufacturer's Specification</th>
<th>Fuel to Use (per Table 3)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absence of Declaration</td>
<td>Regular Fuel</td>
<td>Assumed to be (R+M)/2 method.</td>
</tr>
<tr>
<td>Minimum of 87 Octane</td>
<td>Regular Fuel</td>
<td></td>
</tr>
<tr>
<td>Regular Fuel</td>
<td>Regular Fuel</td>
<td></td>
</tr>
<tr>
<td>Premium Fuel Recommended</td>
<td>Premium Fuel</td>
<td></td>
</tr>
<tr>
<td>Premium Fuel Required</td>
<td>Premium Fuel</td>
<td></td>
</tr>
<tr>
<td>91+ Octane</td>
<td>Premium Fuel</td>
<td>Assumed to be (R+M)/2 method.</td>
</tr>
<tr>
<td>Premium Recommended When Towing</td>
<td>Regular Fuel</td>
<td>Towing is a small subset of customer usage.</td>
</tr>
<tr>
<td>Flex Fuel with Gasoline or E85</td>
<td>Recommended Gasoline</td>
<td>Use the gasoline rating if E85 rating is</td>
</tr>
<tr>
<td></td>
<td>E85 (conditional)</td>
<td>within 2%. If E85 rating is more than 2%</td>
</tr>
<tr>
<td>Mid-Grade Fuel Recommended</td>
<td>Mid-Grade Fuel</td>
<td>Premium not allowed.</td>
</tr>
</tbody>
</table>

5.3 Reference CI Fuel Specifications

Reference fuel specifications are defined by Title 40, Code of Federal Regulations, Part 86.1313-87, and represent range mean values for Type 2-D diesel fuel. The reference fuel characteristics in Table 4 have been determined to affect engine test power, and are listed with the applicable test ranges for which correction factors are valid.

<table>
<thead>
<tr>
<th>TABLE 5 - REFERENCE CI FUEL SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Condition</td>
</tr>
<tr>
<td>Fuel Density at 15 °C</td>
</tr>
<tr>
<td>Fuel Kinematic Viscosity at 40 °C</td>
</tr>
<tr>
<td>Fuel Inlet Temperature</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Observed engine power is also corrected for variations in lower heating value (LHV) based on an empirical relationship between LHV and fuel density per 5.6.2.2.

5.4 Alternative Fuels

Reference values for alternative SI and CI fuels, both liquid and gaseous, are not presented in this document. Therefore, when alternative fuels are used for the net power engine test, no corrections to reference fuel conditions shall be made. Any reference to the rated power and torque for an engine rated on alternative fuel should specify the fuel used in rating the engine.

5.5 Power Correction Factor

The performance of SI and CI engines is affected by the density of the inlet combustion air as well as by the characteristics of the test fuel. Whenever possible, tests should be run at the standard conditions with reference fuels. When this is not possible, in order to provide a common basis of comparison, correction factors should be applied to the observed net power and torque to account for differences between reference air and fuel conditions and those at which the test data were acquired.
5.5.1 All power and torque correction procedures for atmospheric air are based on the conditions of the engine inlet air supply immediately prior to the entrance into the engine air induction system. This may be ambient (atmospheric) air or a laboratory air plenum that maintains air supply conditions within the range limits defined per 5.1. Air supply systems that provide tuning or pressure charging in violation of the intent of this procedure are prohibited.

5.5.2 On any engine where the power output is automatically controlled to compensate for changes in one or more of the listed inlet air and fuel supply test conditions, no correction for that test parameter shall be made. For example, boosted engines with absolute pressure controls shall not be corrected for ambient barometric pressure.

5.5.3 The magnitude of the power correction for tests run at non-standard conditions should not exceed 3% for inlet air or 3% for inlet fuel corrections. If the correction factor exceeds these values, it shall be noted as a nonstandard test in accordance with 8.1.

5.6 Correction Formulas

The applicable correction formulas for spark ignition and compression ignition engines are listed in this section. These correction formulas are designed for correction of net brake power at full throttle operation; however, for CI engines the formulas may also be used to correct partial load power for the purpose of determining specific fuel consumption. These correction formulas are not intended for altitude de-rating. This section includes all formulas necessary to correct observed engine power performance for deviations in inlet air and fuel supply conditions.

5.6.1 Spark Ignition Engine Correction Formulas

These spark ignition engine correction formulas are only applicable at full (WOT) throttle positions.

\[ B_{p_t} = I_{p_t} - F_{p_t} \]  \hspace{2cm} (Eq. 1)

where:

\[ I_{p_t} = CA \times I_{p_t} - CA \times (B_{p_t} + F_{p_t}) \]  \hspace{2cm} (Eq. 2)

and the atmospheric correction factor, CA, is defined as:

\[ CA = \left( \frac{99}{P_{a_0}} \right)^{\frac{t_3 - 273}{298}} \]  \hspace{2cm} (Eq. 3)

If friction is measured then brake power can be calculated by combining Eqs. 1 and 2:

\[ B_{p_t} = CA \times B_{p_t} + (CA - 1) \times F_{p_t} \]  \hspace{2cm} (Eq. 4)

If friction is not measured and 85\% mechanical efficiency is assumed per 3.7 then:

\[ F_{p_t} = \frac{(1 - ME) \times B_{p_t}}{ME} = \frac{(1 - 0.85) \times B_{p_t}}{0.85} = 0.176 \times B_{p_t} \]  \hspace{2cm} (Eq. 5)

Brake power assuming 85\% mechanical efficiency can then be calculated by substituting Eq. 5 into Eq. 4:

\[ B_{p_t} = (1.176 \times CA - 0.176) \times B_{p_t} \]  \hspace{2cm} (Eq. 6)

NOTE If a lab auxiliary charge air cooler is used in conjunction with the standard test method per 6.2.3, no inlet air temperature corrections shall be made. In this case, the temperature correction exponent becomes zero. Otherwise use Eq. 3.
5.6.2 Compression Ignition Engine Correction Formulas

These CI engine correction formulas are applicable at all speed and load levels

\[ B_{p_c} = (CA \times \text{CF}) \times B_{p_a} \]  

(Eq. 7)

5.6.2.1 Calculation of Atmospheric Correction Factor, CA

\[ CA = (Fa)^{\frac{\alpha}{\beta}} \]  

(Eq. 8)

where:

\[ Fa = \left( \frac{Pa_{aw}}{Pa_{aw}} \right)^{\frac{1}{t_c + 273}} \times \left( \frac{99}{298} \right)^{\frac{t_c + 273}{298}} \]  

(Eq. 9)

and values for \( \alpha \) and \( \beta \), are summarized in Table 6:

<table>
<thead>
<tr>
<th>Pressure Charging System</th>
<th>Charge Air Cooling System</th>
<th>( \alpha )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturally Aspirated</td>
<td>None</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Mechanicaly Supercharged</td>
<td>All</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>None</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>Air-to-Air</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>Jacket Water</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>Lab Auxiliary (Standard)</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Turbocharged</td>
<td>Lab Auxiliary (Optional)</td>
<td>0.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Where "standard" and "optional" refer to the lab auxiliary cooler test method described in 6.2.3.

The value of the engine factor \( fm \) is determined from Table 7:

<table>
<thead>
<tr>
<th>( \frac{Q}{R} )</th>
<th>( FM )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt; 37.2 )</td>
<td>0.2</td>
</tr>
<tr>
<td>( 37.2 \leq \frac{Q}{R} &lt; 65 )</td>
<td>( 0.036 \times \frac{Q}{R} - 1.14 )</td>
</tr>
<tr>
<td>( 65 \leq \frac{Q}{R} )</td>
<td>1.2</td>
</tr>
</tbody>
</table>

where:

\( Q = 120 \, 000 \times F(D \times N) \) for four-stroke engines

\( Q = 60 \, 000 \times F(D \times N) \) for two-stroke engines

\( R = \frac{P_{m,c}}{P_{a,c}} \) for all engines \((R = 1 \text{ if naturally aspirated})\)
5.6.2.2 Calculation of Fuel Correction Factor, CF

\[ CF = F_d \times F_v \]  \hspace{1cm} (Eq. 10)

where:

\[ F_d = 1 + 0.70 \left( \frac{S_{G_b} - S_{G_o}}{S_{G_o}} \right) = 1 + 0.70 \left( \frac{0.850 - S_{G_b}}{S_{G_o}} \right) \]  \hspace{1cm} (Eq. 11)

and:

\[ F_v = \frac{1 + S / V_o}{1 + S / V_e} = \frac{1 + S / V_o}{1 + S / 2.6} \]  \hspace{1cm} (Eq. 12)

NOTE: The previous equations correct observed power to reference fuel density and viscosity levels. A correction coefficient of 0.70 in the previous density factor equation is added to account for typical changes in lower heating value at differing density levels, based on an empirical LHV-SG relationship.

Values of \( S \) shall be determined by the engine manufacturer. If no values are available, the following shall be used:

a. Pump/Line/Nozzle Systems—0.15
b. Unit Injectors—0.0
c. Common Rail—0.15

NOTE: If used for the purpose of determining specific fuel consumption, the corrected fuel flow is given by the following

\[ F_c = (S_{G_b} / S_{G_o} \times F_v) F_o \]  \hspace{1cm} (Eq. 13)

Correction Formulas Prepared By the SAE Power Test Code Committee

6. LABORATORY AND ENGINE EQUIPMENT

This section contains a list of laboratory and engine equipment used in the net power and torque test.

6.1 Engine Equipment

A "fully equipped" engine, as defined in 3.5, is required for the net power and torque test. Table 8 lists the engine accessories and control settings that are required for this test.
<table>
<thead>
<tr>
<th>System</th>
<th>Required</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Air Induction System</td>
<td>Yes</td>
<td>The complete Air Induction System including all active or passive tuning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and/or noise attenuation devices is required. The Air Induction System</td>
</tr>
<tr>
<td>Air Ducting</td>
<td>Yes</td>
<td>begins at the point where air</td>
</tr>
<tr>
<td>Air Cleaner</td>
<td>Yes</td>
<td>enters the atmosphere and ends at the entrance to</td>
</tr>
<tr>
<td>Air Preheat</td>
<td>No</td>
<td>the throttle body, inlet manifold, or turbocharger inlet, on</td>
</tr>
<tr>
<td>Active Tuning Device</td>
<td>Yes</td>
<td>engines as appropriate</td>
</tr>
<tr>
<td>2. Pressure Charging System</td>
<td>Yes</td>
<td>For all engines equipped with variable boost as a function of the other</td>
</tr>
<tr>
<td>Boost Control Settings</td>
<td></td>
<td>engine parameters (speed/load/fuel octane, etc.), the boost pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>controls must be set to reflect intended in-service operation.</td>
</tr>
<tr>
<td>3. Charge Air Cooling System</td>
<td>Yes</td>
<td>If applicable.</td>
</tr>
<tr>
<td>Charge Air Cooler</td>
<td>Yes</td>
<td>See 6.2.3 for laboratory auxiliary cooler provisions.</td>
</tr>
<tr>
<td>Cooling Pump or Fan</td>
<td>Conditional</td>
<td>If active at rated conditions.</td>
</tr>
<tr>
<td>4. Electrical System</td>
<td>Yes</td>
<td>Required if standard equipment in the application. A generator/alternator</td>
</tr>
<tr>
<td>Ignition System</td>
<td>Yes</td>
<td>shall operate at a load level sufficient to power only the required</td>
</tr>
<tr>
<td>Starter</td>
<td>No</td>
<td>components (i.e., fuel injectors, ignition system, electronic controller,</td>
</tr>
<tr>
<td>Generator/Alternator</td>
<td>Conditional</td>
<td>electric fuel pump, cooling fans, coolant pumps). If an auxiliary power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>supply is used, the actual generator/alternator load for the required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>components must be determined and the generator/alternator input</td>
</tr>
<tr>
<td></td>
<td></td>
<td>required to produce that power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>subtracted from the measured torque and power data. See 6.2.4 for</td>
</tr>
<tr>
<td></td>
<td></td>
<td>laboratory equipment provisions.</td>
</tr>
<tr>
<td>Ignition Timing Control Settings</td>
<td>Manufacturer's Specification</td>
<td>For any engine equipped with electronic controls and/or knock sensors, the spark or timing advance shall reflect intended in-service operation. See 7.5</td>
</tr>
<tr>
<td>5. Emissions Control System</td>
<td>Yes</td>
<td>All control settings or adjustments must be set to reflect intended</td>
</tr>
<tr>
<td>Fuel Filters/Prefilters</td>
<td>Optional</td>
<td>See 6.2.2 for laboratory fuel supply system provisions.</td>
</tr>
<tr>
<td>Fuel Supply Pump</td>
<td>Yes</td>
<td>Or equivalent electrical load if applicable.</td>
</tr>
<tr>
<td>Injection Pump/Carburetor or Fuel</td>
<td>Manufacturer's Specification</td>
<td>Control settings must reflect intended in-service operation.</td>
</tr>
<tr>
<td>Metering Control Settings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Engine Cooling System (Liquid)</td>
<td>Yes</td>
<td>Functionally equivalent laboratory system recommended.</td>
</tr>
<tr>
<td>Cooling Pump</td>
<td>Yes</td>
<td>Production intent thermostat required. Blocked open thermostat is</td>
</tr>
<tr>
<td>Radiator</td>
<td>Optional</td>
<td>recommended.</td>
</tr>
<tr>
<td>Thermostat</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 8 - ENGINE EQUIPMENT (CONTINUED)

<table>
<thead>
<tr>
<th>System</th>
<th>Required</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Fan</td>
<td>Optional</td>
<td>Cooling fans represent a significant parasitic load on an engine and must be considered in rating power and torque. A fan used in dynamometer testing shall be mounted behind a radiator with the same shrouding as in the application for which it is being rated. For applications in which the cooling fan runs less than 20% of the time during operation at the rated power conditions, the fan may be run in its minimum power setting. For all other applications, at each engine speed, a variable fan should be run at the minimum fan power required to provide steady-state cooling of the engine at maximum brake load when operated at reference atmospheric conditions. NOTE: If the fan is omitted for dynamometer testing, the minimum allowable fan power as described above should be determined and subtracted from the net brake power.</td>
</tr>
<tr>
<td>Engine Cooling System (Air)</td>
<td>Yes</td>
<td>See previous comments same as liquid cooling fan.</td>
</tr>
<tr>
<td>Blower</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>8. Lubrication System</td>
<td>Yes</td>
<td>The fully equipped engine closed loop lubrication system is used. Oil fill shall be at manufacturer's full level as indicated on the dip stick. Oil temperatures shall reflect in-service levels at reference test conditions. The production oil pan is mandatory.</td>
</tr>
<tr>
<td>9. Exhaust System</td>
<td>Yes</td>
<td>See 6.2.1 for exhaust system laboratory equipment provisions.</td>
</tr>
<tr>
<td>10. Engine Driven Auxiliary Devices</td>
<td>Conditional</td>
<td>Required if standard equipment. It is permissible to run without a specific accessory and subtract the parasitic loss of the accessory from the engine brake output.</td>
</tr>
<tr>
<td>Power Steering Pump</td>
<td>Conditional</td>
<td>Plumb fully operational pump for minimum parasitic loss at rated speed.</td>
</tr>
<tr>
<td>Air Conditioning Compressor</td>
<td>Conditional</td>
<td>Should be de-clutched</td>
</tr>
<tr>
<td>Vacuum Pumps</td>
<td>Conditional</td>
<td>Required only if needed to drive other required systems listed, and it functions in that capacity more than 20% of engine running time during intended in-service operation at rated power condition.</td>
</tr>
<tr>
<td>Air Compressors</td>
<td>Conditional</td>
<td>See previous comments - same as vacuum pumps.</td>
</tr>
<tr>
<td>Auxiliary Hydraulic Pump</td>
<td>Conditional</td>
<td>If required for engine operation or if standard equipment.</td>
</tr>
<tr>
<td>11. Transmission</td>
<td>No</td>
<td>The correction of engine power or torque for transmission losses is not permitted.</td>
</tr>
</tbody>
</table>
6.2 Laboratory Equipment

The following provisions are made for use of standard laboratory test equipment for the net power test:

6.2.1 Exhaust System

A complete series production Exhaust System (including mufflers, active catalytic converters, resonators) or any laboratory system that provides equivalent restriction at the peak power engine speed. If a complete vehicle exhaust system is not used, the laboratory system must include the vehicle system at least through the first major restriction or reflection point for tuning (e.g., close-coupled catalytic converter). It is strongly recommended that a full vehicle exhaust be used with four-cylinder engines that are typically most sensitive to exhaust system tuning. Procedures for determining application specific exhaust backpressure are given in Section 9. In order to run tests on the dynamometer, a catalytic converter with an inert substrate may be used. It is also permissible to replace the converter substrate with a perforated plate providing the same restriction as the converter substrate located in the converter housing at the location of the leading edge of the substrate. Manufacturers who elect to use a perforated plate in place of an inert substrate must verify that the backpressure during dynamometer testing is equivalent to that observed in the production application.

6.2.2 Fuel Supply System

Any laboratory system that provides a supply of fuel to the fuel inlet of the fully equipped engine is acceptable. Fuel supply pressure should be controlled to application specific values. The fuel supply system must be capable of controlling fuel supply temperature to within the ranges specified in 5.3 for CI engines. The fuel supply system shall not exceed the manufacturer’s maximum permissible restriction requirements, if applicable.

6.2.3 Charge Air Cooler

A Charge Air Cooler is recognized to have a significant impact on engine performance. For this reason, to obtain an accurate measure of rated engine power for all engines equipped with a Charge Air Cooler, the charge air temperature and pressure at the outlet of the Charge Air Cooler must be set to reflect in-service operation at standard inlet conditions. For charge-cooled engines, use of the production Charge Air Cooler is preferred, however, a laboratory auxiliary cooler may be employed for test purposes. The test methods required to control the auxiliary lab charge air cooler are defined in 7.5.5.

6.2.4 Auxiliary Power Supply

Even when an alternator/generator is installed, electrically driven engine components determined to be part of the basic engine may be operated via an external power supply. In such cases, the alternator/generator input power required to generate the electrical load must be determined and subtracted from the corrected net brake power.

7. LABORATORY TEST PROCEDURES

7.1 Instrumentation Accuracy

The following minimum test instrumentation accuracy is required:

a. Torque±0.5% of measured value
b. Speed±0.2% of measured value
c. Fuel Flow±1% of measured value
d. General Temperature measurements±2 °C
e. Inlet Air Temperature±1.0 °C
f. Air Supply Pressure—±0.1 kPa

g. Other Gas Pressures—±0.5 kPa

7.2 Measurement Requirements

7.2.1 Inlet Air Supply Pressure and Temperature

Pressure and temperature of the inlet air supply, used for the purpose of correcting engine power, shall be measured in a manner to obtain the total (stagnation) condition at the entrance to the engine air induction system. This measurement shall be made within 0.15 m of the entrance to the Air Induction System inlet duct. On those tests where the engine air supply is ambient air, this pressure is the barometric pressure; on those tests where the air supply is test cell ambient air, this pressure is the cell barometric pressure; on those tests where the inlet air supply is plumbed directly to the Air Induction System, the correction pressure is the pressure measured inside the lab plenum.

7.2.2 Intake Manifold Pressure and Temperature

Intake manifold pressure and temperature shall be measured as static values with probes located in a section common to several cylinders. In such installations, dynamic pressure is assumed zero.

7.2.3 Charge Air Cooler Pressure and Temperature

For engines equipped with a charge air cooler, instrument the engine with thermocouples and pressure probes midstream at the air inlet and outlet of the Charge Air Cooler. On charge air-cooled engines in which a laboratory cooler is employed for testing, pre-cooler charge air pressure must also be measured for the purpose of setting in-service restrictions per 7.5.5. Pre-cooler pressure must be measured upstream of the auxiliary unit in a manner to obtain the total (stagnation) value. Auxiliary cooler restriction is the difference between the pre-cooler and intake manifold pressures.

7.2.4 Coolant Temperature

Coolant temperature in liquid-cooled engines shall be measured at the inlet and outlet of the engine, in air-cooled engines at points specified by the manufacturer.

7.2.5 Oil Pressure and Temperature

Oil pressure shall be measured at the entrance to the main oil gallery. Oil temperature can be measured at the same location or inside the oil sump.

7.2.6 Fuel Temperature and Pressure

Fuel temperature and pressure shall be measured at the inlet to the carburetor or fuel injector rail for SI engines, and at the inlet to the high-pressure injection pump or unit injector rail for CI engines, and at the outlet of the volumetric flow meter for gaseous-fueled engines. Fuel temperature must also be measured at the entrance to the fuel flow meter for the purposes of density correction in the mass fuel flow calculation.

7.2.7 Exhaust System Pressure and Temperature

Exhaust system pressure shall be measured to obtain the total (stagnation) pressure downstream of the exhaust runner collector(s). Exhaust System temperature shall be measured in approximately the same location as the pressure measurement. In the event that the engine is equipped with close-coupled catalytic, the pressure probe can be located downstream of the catalysts. For applications that use laboratory exhaust equipment to mimic backpressure in service (steady state or transient), the pressure probes must be installed in the same location for both the vehicle test and the dynamometer net power test.
7.2.8 Air/Fuel Ratio

The air/fuel ratio shall be measured for the purpose of ensuring that the air/fuel run on the dynamometer is the same as that run in the application.

7.3 Adjustments and Run-In

7.3.1 Adjustments

No component, assembly, or calibration adjustments are allowed during the test.

7.3.2 Run-In

The engine shall be run-in according to the manufacturer’s recommendation. If no such recommendation is available, the engine shall be run-in until friction has stabilized as determined by brake torque readings that are repeatable within 1%.

7.4 Test Operating Conditions

There are two alternative methods for determining the engine control settings and operating conditions used in rating engine power and torque: steady-state and transient.

7.4.1 Steady-State

Steady-state procedures have historically been used for all engine rating. They are still appropriate for engines that usually operate at constant speed and load such as industrial engines, generator sets, small hand-held engines, utility, lawn and garden engines, off-highway vehicles and medium or heavy duty on-highway vehicles. It is acceptable to use steady-state procedures and operating conditions for rating of any engine.

7.4.2 Transient

Power achieved during transient maneuvers such as acceleration from a stop or passing on the highway can be more meaningful to consumers of light duty vehicles than steady-state power. The widespread application of sophisticated electronic controls has provided engine manufacturers with the opportunity to regulate engine operation as a function of time as well as environmental conditions and fuel type. Examples of engine control parameters that may vary with time are variable valve actuation, active intake manifolds, electronic spark control, catalyst protection algorithms, active exhaust controls, variable boost control, electronic throttle control, knock control, traction and vehicle stability control, variable compression ratio, injection timing and pressure. It is the intent of this procedure to rate engine power and torque with these controls set as they would be for the customer in the most likely operating condition.

The method for determining test conditions used for rating engines from light duty vehicles is to obtain and record time synchronized data on all engine control parameters from an engine installed in a vehicle during a transient maneuver and then to duplicate these control settings during steady state engine operation on a dynamometer. The procedure for obtaining these data can be found in Section 9.

7.5 Power and Torque Determination

7.5.1 Test Procedure

This section defines the actual dynamometer test procedure used in obtaining Rated Net Power and Torque. The test shall consist of a run at full throttle for spark-ignited engines and at a fixed full-load fuel injection pump setting for CI engines. The following test controls and operating conditions must be adhered to meet the requirements of this standard:
7.5.2 Test Points

Measurements shall be taken at increments of no more than 500 rpm in sequence from the lowest to the highest engine speeds recommended by the manufacturer. The operating speeds shall include those for peak power and peak torque. Data at 100 rpm increments around peak torque and peak power are recommended to accurately distinguish their respective rated speeds. Engine speed shall not deviate from the nominal set speed by more than ±1% or 5 rpm, whichever is greater.

7.5.3 Logging of Measurements

No data shall be taken until torque and speed measurements have remained stable within 1% and controlled temperatures have remained stable within ±2 °C for at least 1 minute. The recorded measurements shall be the average of readings over a span of 1 minute. Alternatively, data can be taken by stabilizing the torque and speed for 5 seconds and then acquiring data at a minimum 10 Hz rate for at least ten seconds. If this alternative procedure is used, the entire speed sweep shall be repeated at least three times. The results are considered valid if the repeatability of at least three measurements is within 1% of the mean.

7.5.4 Engine Calibration Controls

The engine calibration settings (including spark advance and air/fuel ratio) shall be representative of the in-service controls. For light duty vehicles, the engine control settings can be set to values equivalent to those recorded during the vehicle transient test described in Section 9. Replication of transient control settings used during the steady state power test on dynamometer must include any time-based delays that would occur in the transient vehicle test. Engines equipped with active knock control are required to run at the spark advance established with the minimum octane grade fuel recommended by the manufacturer.

7.5.5 Charge Air Cooler Settings

For any engine equipped with a Charge Air Cooler, the air temperature at the outlet of the Charge Air Cooler must be set to reflect the conditions exhibited during in-service operation. For light duty vehicles, the transient vehicle test procedure described in Section 9 can be used to derive the Charge Air Cooler outlet air temperature at all engine speeds. For all other engine applications, the Charge Air Cooler outlet temperatures should be set to replicate the values exhibited during fully warmed up, steady-state operation. For either of these tests, the Charge Air Cooler temperature shall be maintained within a tolerance of ±2 °C at all engine speeds tested. If no testing was performed to determine the Charge Air Cooler outlet temperature, a fixed charge air cooler outlet temperature of 80 °C can be used.

7.5.6 Boosted Engine Settings

For engines equipped with variable boost as a function of charge or inlet air temperature, octane rating, and/or engine speed, the boost pressure shall be set to replicate the in-service conditions established with the minimum octane fuel recommended by the manufacturer.

7.5.7 Ambient Temperature

Ambient test cell temperature control is not required by this standard.

7.5.8 Inlet Air Conditions

The pressure, temperature, and humidity of the engine’s inlet air supply shall be controlled as close to the standard reference conditions per 6.1 as possible to minimize the correction factor. The inlet air pressure temperature and humidity shall not deviate from the controlled set points by more than 3% for the entire test. If a laboratory plenum is plumbed to the engine for the purpose of controlling inlet air supply conditions, the exhaust backpressure should be referenced to the laboratory plenum pressure rather than the cell ambient pressure.
7.5.9 Coolant Temperature

Coolant temperature, measured at the thermostat location for a liquid-cooled engine, shall be controlled to within \( \pm 3 \, ^\circ C \) of the nominal thermostat control temperature specified by the manufacturer. If no temperature is specified, the coolant temperature shall be controlled to \( 90 \, ^\circ C \pm 3 \, ^\circ C \). Cooling air supply temperature for an air-cooled engine is regulated to \( 35 \, ^\circ C \pm 5 \, ^\circ C \).

7.5.10 Coolant Type

For liquid cooled engines, the type of coolant and water-mix ratio shall match the engine coolant used in series production by the manufacturer.

7.5.11 Oil Temperature

Although oil temperature control is not an expressed requirement of this standard, the oil temperatures run in the dynamometer rating test must be representative of the temperatures exhibited in service with a fully warmed up engine. The temperature must be controlled to a value no greater than the maximum limits specified by the manufacturer.

7.5.12 Oil Type

The type of engine oil used for the test shall match the SAE designated oil type recommended by the manufacturer for the application.

7.5.13 Fuel Temperature

Fuel inlet temperature for diesel fuel injection shall be controlled to \( 40 \, ^\circ C \pm 3 \, ^\circ C \) for unit injector systems, and \( 40 \, ^\circ C \pm 1 \, ^\circ C \) for pump/lube/nozzle systems. Test fuel temperature control is not required on SI engine power tests.

7.5.14 Fuel Pressure

The fuel pressure shall be controlled to match the operating pressure specified by the manufacturer in series production.

7.5.15 Exhaust Backpressure

As indicated in 7.4, for light duty vehicles, the exhaust backpressure can be set to replicate the values measured in a vehicle transient maneuver. For all other applications, if a laboratory exhaust system is used, the exhaust backpressure must be set to replicate the values measured under the steady state conditions exhibited in service. The exhaust backpressure setting used at peak power must match the exact value recorded during in service conditions within \( \pm 1.5 \, \text{kPa} \).

7.5.16 Test Cell Exhaust Venting

The exhaust gas from the engine must be vented to a reservoir having a total pressure within 0.75 \( \text{kPa} \) of the inlet air supply pressure.

8. PRESENTATION OF RESULTS

This section contains a listing of test data to be recorded and procedures for presenting results.

8.1 Reporting Requirements

All reported engine test data shall carry the notation: "Performance obtained and corrected in accordance with SAE J1349 Revised MAR2008. Any deviation from this document, its procedures, or limits shall be noted (e.g., Correction factors used exceed valid range defined in the SAE J1349 Procedure Revised MAR2008). Correction factors determined using assumed mechanical efficiency of 85% rather than actual test data)." The following information is to be provided in the engine power rating report:
8.1.1 General Test Information
   a. Date of test
   b. Engine serial number
   c. Test/run number
   d. Test location and test cell number
   e. Additional engine equipment listed per 6.1

8.1.2 Engine Description
   a. Engine Displacement
   b. Bore and stroke
   c. Number and configuration of cylinders
   d. Ignition type (Spark, Compression)
   e. Combustion cycle (2-Stroke, 4-Stroke)
   f. Fuel system (Carburetion, Throttle Body Injection, Multi-port injection, etc)
   g. Valve train (Push Rod - 2 Valve, Dual Overhead Cam - 4 Valve, Electro-Mechanical, etc)
   h. Pressure charging (naturally aspirated, turbocharged, supercharged)
   i. Charge air cooling (if applicable)
   j. Fan system (Electric, Clutch Driven, Hydraulic, etc)
   k. Knock control system (if applicable)
   l. Manufacturer's recommended minimum fuel octane number

8.1.3 Liquid Fuel - Spark Ignition Engine
   a. Fuel type and/or blend
   b. Research and motor octane numbers
   c. H:C Ratio
   d. Fuel density/specific gravity at 15 °C
   e. Lower heating value

8.1.4 Gaseous Fuel - Spark Ignition Engine
   a. Fuel type or grade
   b. Composition
c. Density at 15 °C and 101 kPa

d. Lower heating value

8.1.5 Diesel Fuels
  a. ASTM or other fuel grade
  b. Density at 15 °C
  c. Viscosity at 40 °C
  d. Lower heating value (optional)

8.1.6 Lubricating Oil
  a. API engine service classification
  b. SAE viscosity grade
  c. Manufacturer and brand name

8.1.7 Engine Coolant
  a. Coolant type
  b. Coolant/Water Mix
  c. Manufacturer and brand name

8.1.8 Test Cell Measurements and Calibrations
  a. Test cell venting pressure for exhaust system
  b. Load cell calibration
  c. Pressure transducer calibrations
  d. Thermocouple and/or Resistance Temperature Detector/Platinum Resistance Thermometer calibrations
  e. Fuel flow meter calibration
8.2 Test Data Requirements

All reported or advertised test data bearing the SAE J1349 notation shall include a minimum of the following parameter measurements and calculations at each test point:

**TABLE 8 - TEST DATA PARAMETERS**

**Measurements**
- Engine Speed (may be obtained from engine controller)
- Observed Brake Torque
- Friction Torque
- Air/Fuel Ratio
- Spark Advance / Ignition Timing (may be obtained from the engine controller)
- Ambient Temperature and Pressure
- Inlet Air Temperature and Pressure
- Inlet Air Water Vapor Pressure
- Intake Manifold Air Temperature and Pressure (may be obtained from engine controller)
- Temperature of Fuel at Fuel Flow Meter
- Fuel Rail Temperature and Pressure
- Engine Coolant Inlet and Outlet Temperature (water cooled engines only)
- Oil Sump Temperature and Oil Gallery Pressure
- Exhaust Gas Temperature at the manifold outlet (Left & Right)
- Exhaust Pressure at the manifold outlet (Left & Right)
- Smoke (optional—CI engines only)

**Calculations**
- Corrected Torque (nearest whole number above 25 lb-ft, below 25 lb-ft, it is permissible to rate to the nearest 0.1 unit)
- Observed BMEP
- Corrected BMEP
- Observed Brake Power
- Corrected Brake Power (nearest whole number above 25 hp, below 25 hp it is permissible to rate to the nearest 0.1 unit)
- SAE J1349 Correction Factor (reported to four significant digits)
- Mass Air Flow (May be measured directly or calculated from fuel flow and A/F Ratio measurements)
- Volumetric Fuel Flow
- Mass Fuel Flow
- Brake Specific Fuel Consumption

**Boosted Engine Parameters**
- Boost Pressure
- Intercooler Inlet and Outlet Air Temperature and Pressure
- Compressor Inlet and Outlet Temperature and Pressure
- Turbine Inlet and Outlet Temperature and Pressure
- Charge Air Cooler Efficiency

**Engine Controller Parameters (If Available)**
- Manifold Absolute Pressure (MAP) or Total Mass Airflow (as applicable)
- Spark Advance/Ignition Timing
- Injection timing (Diesel)
- Desired/Commanded Air/Fuel Ratio
9. TRANSIENT VEHICLE TESTING

Steady-state engine control settings, exhaust system backpressure, and charge air cooler efficiency may apply to all engines if so chosen, but must be used for engines installed in on-road vehicles over 8500 lb GVW (medium-duty or heavy-duty truck engines), and engines that usually operate at constant speed and load such as (but not limited to) industrial engines, generator sets, small hand-held engines, utility, lawn and garden engines, and engines used in off-highway vehicles.

Any engine may be tested using the steady-state conditions defined above. It is simpler and requires less equipment, time and testing. But it should be understood that engines which operate at continuously varying speeds and loads (i.e. light duty vehicles) create many transient effects related to heat transfer and the properties of various materials at different temperatures. These transient effects may permit the creation of control algorithms that temporarily increase brake horsepower and are representative of the power the end-user would obtain under similar, transient conditions. The traditional, steady-state test condition may yield lower net brake horsepower and torque for the same engine.

For some applications, an engine’s exhaust backpressure and time dependent control settings that occur during transient maneuvers can be used in testing to provide a more representative measure of the engine performance that the customer will receive in service. The transient vehicle test specifications and procedures described in the following sub-sections can be applied to all engines used to propel vehicles below medium-duty trucks, the dividing line being 8500 lb GVW. This group includes, but is not limited to: snowmobile engines, passenger car engines, light truck engines, and all terrain vehicle engines.

9.1 Transient Vehicle Test Specifications

9.1.1 Vehicle Equipment

The test must be conducted with a vehicle matching as closely as possible the intended design for series production. Exhaust system and charge air cooler design and engine mass flow must match production intent. Slight deviations are allowable as are typical of pre-production parts.

9.1.2 Vehicle Weight

Empty vehicle weight plus full tank of the fuel recommended by the manufacturer for customer use, driver, and test equipment.

9.1.3 Exhaust Pressure Measurement

Instrument the vehicle with pressure probe(s) installed downstream of the exhaust runner collector for each exhaust manifold. The same method and location of exhaust pressure measurement used in the vehicle must be used in the subsequent dynamometer net power test to set exhaust backpressure. For turbocharged engines, backpressure must be measured downstream of the turbine.

9.1.4 Charge Air Cooler (if applicable)

For engines equipped with a Charge Air Cooler, instrument the engine with thermocouples and pressure probes midpoint at the air inlet and outlet of the Charge Air Cooler.

9.1.5 Method of Data Acquisition

Instrument the vehicle with any suitable data acquisition system to record all engine controller parameters that will be required to replicate the engine’s time-based variable controls on the dynamometer net power test. This may include, but is not limited to: rpm, MAP, mass airflow, spark advance, A/F ratio, cam timing, fuel injector timing and pulse width, EGR (exhaust gas recirculation) valve and throttle position, coolant and oil temperature.
9.1.6 Ambient Conditions

The test must be conducted at the following ambient conditions:

a. Air Temperature: 25 °C ± 10 °C
b. Barometric Pressure: 90 kPa – 105 kPa
c. Humidity: ≤70% relative humidity

NOTE: The purpose of this specification is to prohibit testing at humidity levels high enough to suppress knock such that the spark advance settings determined from the vehicle test would be unrepresentative of the spark advance which a customer would see at standard conditions.

d. Wind speed: less than 7 m/s (15 mph)
e. Road Surface: A closed course, with dry, flat, level hard-paved surface.

9.2 Transient Vehicle Test Procedures

9.2.1 Engine Warm-Up

The engine must be fully warmed up. Run the vehicle at a moderate speed (90 km/h – 100 km/h for road vehicles).

9.2.2 Data Acquisition Rate

All data recorded by the data acquisition system must be recorded at 10 Hz or faster sample rate.

9.2.3 Vehicle Acceleration Test Procedures

For measuring exhaust back-pressure, charge air cooler parameters (when applicable), and time-dependent engine control parameters, the vehicle shall be locked in a fixed gear and accelerated at full load from the lowest stable engine speed in that gear to the engine maximum speed.

Evaporative cooling of charge air coolers is prohibited unless offered by the manufacturer as standard equipment on the engine in the application being rated. If evaporative cooling is used, the evaporative cooling fluid must be as recommended by the manufacturer.

9.2.4 Vehicle Data Averaging

The acceleration test should be repeated at least once and the results averaged for application to the dynamometer net power test.

9.3 Application of Vehicle Transient Data to Net Power Test

The exhaust backpressure, charge air cooler parameters, and engine control parameters shall be determined by averaging the transient vehicle test data for all test runs. The dynamometer net power test shall be controlled at each speed set point to the averaged parameters recorded during the vehicle test. The exhaust backpressure applied to the dynamometer net power test can be set with a valve or orifice plate sized and located to match the average vehicle transient backpressure at the engine’s peak power speed.

For charge-air-cooled engines, the charge air cooler outlet temperature shall be adjusted for the ambient temperature recorded during the vehicle tests by increasing or decreasing the charge air cooler outlet temperature by the same amount that the ambient conditions for the vehicle test varied from the standard temperature.
10. NOTES

10.1 Marginal Indicia

A change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

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