An Alternative Use of Crude Glycerin in Canadian Wood Pellet Industry

Murari Mohon Roy and Antonio F. G. Da Silva

Abstract- With the biofuel mandate and government incentives in different countries, there is a sharp rise in world biodiesel production that has created an excessively abundant supply of crude glycerin, which is a by-product of the transesterification process. Although pure glycerin has many valuable uses in the food, pharmaceutical and cosmetics industries, crude glycerin from biodiesel production cannot be directly used for these purposes. This study investigated an alternative use of crude glycerin in Canadian wood pellet industry. Crude glycerin is produced as a by-product of biodiesel production from canola oil, and is soaked in four different types of wood pellets available in Canadian market at different soak temperatures and times to test the rate of glycerin soaking by the wood pellets. Physical properties such as bulk density, durability, fines, etc. are tested according to the Pellets Fuel Institute standard specifications for residential/commercial densified fuel. Fuel properties are measured by ultimate and proximate analyses for wood pellet samples without and with glycerin-soaking. Finally, a wood pellet stove is tested to compare the emissions of CO₂, HC, NOx and CO₂ between pure and glycerin-soaked wood pellets.

Index Term- Crude glycerin, Canadian wood pellet industry, Glycerin soaking in wood pellets, Fuel characterization, Wood pellet stove, Emissions.

I. INTRODUCTION

There has been increasing interest in recent years in the use of biodiesel as a substitute for petroleum-based diesel fuel, because biodiesel offers many advantages such as a higher cetane number, reduced emissions of particulate matter (PM), unburned hydrocarbon (HC), carbon monoxide (CO), reduced toxicity, improved safety, and lower lifecycle carbon dioxide (CO₂) emissions. Several countries including Canada have already started substituting fossil diesel with biodiesel. The US EPA conducted a comprehensive analysis of biodiesel exhaust emissions, showing that pure biodiesel can reduce HC emissions by as much as 70%, and PM and CO emissions by approximately 50% when compared with conventional diesel fuel [1]. These emissions improvements and the drive to move toward renewable energy sources led to the European Parliament and of the Council Directive 2009/28/EC [2], which endorsed that each member state shall ensure that the share of energy from renewable sources in all forms of transport in 2020 will be at least 10% of the final consumption of energy in transport. In December 2006, the Government of Canada announced that it would regulate the renewable content of diesel fuel so that at least 2% biodiesel content would be required by 2012. This 2% fuel blend is referred to as B2. The canola industry has proposed 5% renewable content (B5) by 2015 [3].

Canadians currently consume >26 billion liters of diesel fuel per year, therefore the mandate of 5% biodiesel for 2015 would require an annual production of 1.3 billion liters of biodiesel. In general, for every 100 tons of biodiesel produced, approximately 10 tons of crude glycerin are created (10% by mass). At a rate of 10%, approximately 120,000 tons crude glycerin will be produced from 1.3 billion liters of biodiesel production. In recent years, the price of crude glycerin has been as low as 5.5-11 cents/kg [4]; and because this crude glycerin is expensive to purify for use in the food, pharmaceutical, or cosmetics industries, biodiesel producers must seek alternative methods for its disposal or value-added uses.

Various methods for disposal and utilization of this crude glycerin have been attempted, including combustion, composting, anaerobic digestion, animal feeds, and thermochemical/biological conversions to value-added products. Although glycerin has a moderate heating value, its auto-ignition temperature (370°C) is much higher compared to kerosene (210°C) and gasoline (280°C) [5], so it flames up with difficulty. Another consideration highlighted by Bohon [6] is that when glycerin is heated around 280°C, toxic acrolein is produced by thermal decomposition of glycerin. This is an important factor preventing adoption of combustion as a glycerin disposal or fuel use method by the majority of the biodiesel producing community. To address this incomplete combustion problem, use of a refractory burner has been proposed by Bohon et al. [7]. They attempted the combustion of crude glycerin in a burner designed for retrofit applications in commercial-scale fire-tube package boilers. A stable 100% glycerin combustion was achieved, however, much higher fly ash compared to residual fuel oils combustion was noticed. Another attempt by McNeil et al. [8] to combust glycerin in diesel engines required intake air temperature to be increased to as high as 200°C. Therefore, although liquid glycerin has a potential to be combusted in burners and engines, design modifications are required for proper operations. It has also been suggested that glycerin can be composted [9] or used to increase the biogas production of anaerobic digesters [10]. As a supplement in the diet of growing pigs, crude glycerin had a metabolizable-to-digestible energy ratio similar to corn or soybean oil, however little is

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known about the health effects of impurities in the glycerin [11]. Similarly, broiler chickens fed 2.5–5% glycerin diets had higher breast yield than a control group, but effects of methanol impurities in glycerin require further study [12]. Glycerin can be thermochemically converted into propylene glycol, acetol [13] or a variety of other products [4, 14]. Crude glycerin can also serve as a substrate in conversions mediated by biological processes like fermentation. For example, fermentation of glycerin by the bacterium Escherichia coli produces a mixture of ethanol, succinate, acetate, lactate and hydrogen [15]. Glycerin can also be fermented to citric acid by the yeast Yarrowia lipolytica [16]. Researchers at Virginia Polytechnic Institute are developing algal fermentation processes to convert crude glycerin into high value omega-3 polyunsaturated fatty acids [17]. A new area of research is to make use of the glycerol waste stream from biodiesel production by mixing crude glycerol with waste carbon-rich biomass to create another renewable substitute for fossil fuels and improve the economics of biodiesel production. Palm fibre, fronds and shells have been used as raw materials to produce pelletized fuel, which was mixed with waste glycerol and water [18, 19]. A cost analysis has shown that the cost of pelletized fuel is lower than the typical cost of coal [19]. In order to create an effective energy source, Brady et al. has explored the combining of two waste streams, biomass and biodiesel waste glycerin, to form an energy source that is equivalent to refuse derived fuels (RDFs) in energy content [20].

The main objective of this study is to find an alternative value-added use of crude glycerin. Adding glycerin to wood pellets is a solution because Canada has the largest potential in wood pellet production around the world. Currently Canada has a strong wood pellet industry and as of 2010 its annual production capacity is 2.1 million tons and expected to reach 3.6 million tons in the next few years [21]. The current wholesale price of wood pellets in Canadian market is $0.3–$0.5 per kilogram and the retail price per kilogram is $0.5–$0.7. 120,000 tons of crude glycerin can easily be consumed if mixed with 2.1 million tons of wood pellets at the rate of approximately 6% to produce glycerin-mixed wood pellets or if mixed with projected 3.6 million tons of wood pellets at the rate of approximately 3.5%. This will create additional revenue from 120,000 tons of crude glycerin through converting it into value-added products. Furthermore, this mix would be advantageous since glycerin has a higher heating value than that of wood pellets.

II. MATERIAL AND METHODS

In this study, crude glycerin is produced in the laboratory as a by-product of biodiesel production. The most commonly used method of biodiesel production is the transesterification (alcoholysis) of oil (triglycerides) with methanol in the presence of a catalyst, which gives biodiesel and glycerin (by-product). The basic biodiesel reaction and flow chart of biodiesel production is illustrated in Fig. 1. The procedure to make biodiesel followed in this study is similar to that described in [22]. ASTM 6751 method was used to determine the quality of biodiesel. All the properties were satisfactory according to ASTM limit [23]. To produce biodiesel, canola oil is used as feedstock. Canola oil was purchased from a local supermarket. Two main ingredients for biodiesel production were methanol and sodium hydroxide that were purchased from Canadawide Scientific Ltd. Figure 2 shows the overall flow chart of the test.

A. Pellets and Soaking Test

Four types of wood pellets, two hardwood pellets (Type A and Type B) and two softwood pellets (Type C and Type D) as shown in Fig. 3 are used in the glycerin soaking test. Hardwood pellets were purchased from Canadian supermarket and softwood pellets were collected from Forestry Lab, Faculty of Natural Resources Management, Lakehead University. For soaking test, an electronic balance, a thermometer, a stop watch, a container, a hair drier and a strainer are used as major equipment. Soaking tests were performed at four different soaking times (1, 5, 10 and 20 min) and at six different soaking temperatures (20, 30, 40, 50, 60 and 70°C). About 10 grams of wood pellets are dipped in crude glycerin to soak glycerin in it for different times and temperatures and dried naturally and by forced convection using a hair drier. During the drying process mass of the glycerin-soaked pellets were measured at a certain interval until getting the two consecutive constant readings. The following formula is used to measure the rate of glycerin soaking by the wood pellets.

\[
\text{Rate of soaking (\%)} = \left( \frac{m_2-m_1}{m_1} \right) \times 100
\]

where \(m_1\) is the mass of the wood pellets without glycerin soaking and \(m_2\) is the mass of the glycerin-soaked wood pellets.

B. Viscosity Test

Crude glycerin’s viscosity was also determined at different temperatures to explain different rates of soaking. A Canon-Fenske glass capillary viscometer (No. 400) with accuracy of \(\pm 0.2\%\) and viscometer constant of 1.154 was used that allows ASTM D445 kinematic viscosity testing method.
Fig. 1. Transesterification reaction (a) and flow chart of biodiesel production (b)
C. Pellets Fuel Institute Standard Test

The pure wood pellets and glycerin-soaked wood pellets were analyzed by the PFI Standards 2011 [24]. Table 1 shows different parameters of PFI standard and their limit. Fuel properties that were analyzed are bulk density, diameter, durability, fines, inorganic ash, length, moisture, and chloride. Bulk density is the fuel mass per unit volume of the fuel sample and it is determined in accordance with ASTM E 873. The average diameter of the fuel pellets in the fuel sample is measured by selecting 5 pellets randomly out of the pellet sample being evaluated and measured the diameter of each pellet with a Vernier caliper capable of measuring fuel diameter and length to within 0.001 in. (0.025 mm). Pellet Durability Index (PDI) is a standardized parameter for specifying the ability of the fuel pellets to resist degradation caused by shipping and handling. Pellet durability was determined by using the method outlined by Kansas State University - Mechanical Durability of Feed Pellets, Call Number: LD2668.T4 1962 Y68. Fines is the percentage of fuel material in the fuel sample passing through a 1/8 inch (3.18 mm) screen when the fuel is sampled. It is determined according to PFI standard and all weight measurements were recorded to the nearest 0.1 gram. The percent of fines was calculated to the nearest 0.01% as follows:

\[
\% \text{ Fines} = \left( \frac{\text{Weight of Base Pan} + \text{Fines} - \text{Weight of Base Pan}}{\text{Initial Sample Weight}} \right) \times 100
\]

It should be noted that the pellets remaining after performing the fines determination as specified in fines test can be used without further preparation to conduct the durability test. Inorganic ash indicates the percent inorganic material in the fuel sample and determined in accordance with ASTM D 1102. Length parameter implies that the pellet sample satisfies the minimum required length of 1.5 inches (38 mm). The same Vernier caliper that was used for diameter measurement was used to measure the length of the pellets.
The moisture content of the as-received fuel sample was measured in accordance with ASTM E 871. Along with the moisture and ash test, a test was made for fixed carbon and volatile matter by proximate analysis in accordance with the ASTM E870 and ASTM E872, respectively. An elemental analysis was completed too, which determined the quantity of C, H, N, S, O and Cl in the wood pellets. Following the tests for PFI standards, a heating value test for samples was done in accordance with ASTM E711.

**D. Emission Test**

An emission test was performed to compare the emissions of the pure and glycerin-soaked wood pellet samples. The tests were conducted using a free-standing wood pellet stove model J2000. Its BTU rating was 6000-45,000 BTU/h (1.75-13 kW). Emissions reading were taken after 20 min of running of the stove, when there were almost no fluctuations in emissions and temperatures (front panel and exhaust). Two Type K thermocouples with resolution of 0.1˚C and accuracy of ± (0.1% of reading + 1˚C) were used to measure the stove’s front panel temperature (Fig. 4). Another ultra-fast response Type K thermocouple with resolution of 0.1˚C and range of 260˚C was used to measure the exhaust gas temperatures. A multi-gas analyzer (NOVA Model 7466 PK) and a CO analyzer (Dwyer 1205A) were used to measure the CO, NO, NO₂, HC, CO₂ and O₂ of exhaust gases corresponding to each data point. Gas analyzers’ specifications with methods, resolution, range and accuracy are summarized in Table 2. At every test case, different data were taken for three repetitions and average data is used to plot a graph. Similar front panel temperatures were maintained for all the tests for better comparison of the results.

### III. RESULTS AND DISCUSSION

**A. Soaking Test Result**

**a. Hardwood Pellets**

Firstly, two types of hardwood pellets, which are easily available in Canadian market and mostly used either in barbequing and/or industrial/domestic heating purposes are used. These two types of pellets will be named as Type A (used for barbequing) and Type B (used for heating). Four soaking times and six soaking temperatures were selected for the soaking test with these two pellets. Figure 5 shows the soaking result of Type A pellet. It is seen that rate of soaking increases with the increase in time and temperature. At the temperature of 20˚C, rate of soaking increases from 12% at 1 min to 13% at 20 min soaking time, which is only 1% increase in soaking. At 30˚C, rate of soaking increases from 12% to 16%, when time increases from 1 min to 20 min, which is 4% increase in soaking. At 40˚C, rate of soaking increases from 13% to 19%, this is 6% increase. At 50˚C, increase in soaking is 26%, when time increases from 1 min to 20 min. At 60˚C

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**Table 1**

<table>
<thead>
<tr>
<th>Fuel Property</th>
<th>PFI residential/commercial densified fuel standard</th>
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<tbody>
<tr>
<td>Bulk density (kg/m³)</td>
<td>608.7 - 736.8</td>
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<tr>
<td>Diameter (mm)</td>
<td>5.84 - 7.25</td>
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<tr>
<td>Pellet Durability Index (%)</td>
<td>≥ 95.0</td>
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<tr>
<td>Fines (%)</td>
<td>≤ 1.0</td>
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<tr>
<td>Inorganic ash (%)</td>
<td>≤ 2.0</td>
</tr>
<tr>
<td>Length, % greater than 38.1 mm</td>
<td>≤ 1.0</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>≤ 10.0</td>
</tr>
<tr>
<td>Chloride (ppm)</td>
<td>≤ 300</td>
</tr>
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</table>

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**Fig. 4. Photograph of wood pellet stove with front panel temperature measuring thermocouples**
and 70°C, increase in soaking is 54%, when time increases from 1 min to 20 min, and the maximum soaking is 70%. Figure 6 shows the soaking result of Type B pellet. It is observed that the increase in rate of soaking of Type B pellet is very similar to that of Type A pellet. At 20°C, rate of soaking increases from 15% to 19%, which is 4% increase in soaking. At 30°C, rate of soaking increases again from 15% to 19%, when time increases from 1 min to 20 min. At 40°C, rate of soaking increases from 15% to 24%, which is 9% increase, a slight higher than Type A pellet. At 50°C, increase in soaking is 11%, when time increases from 1 min to 20 min. At 60°C and 70°C, increase in soaking is 46%, when time increases from 1 min to 20 min, and the maximum soaking is 64%.

Comparing Type A and Type B hardwood pellets, it is understood that temperature above 60°C does not help any further soaking, when the soaking time is 20 min. At this time, soaking reaches to its saturation. Furthermore, drying time is determined for natural drying, which was approximately three hours. Drying time is the time required to dry the glycerin of wood pellets, and it is determined, when there was no weight changes in two consecutive readings. A hair dryer was then used to see how fast could be the drying process. There were four settings of the hair dryer, high temperature (60°C), low temperature (45°C), high cool shot and low cool shot options. It was noticed that except the glycerin temperatures of 20°C and 30°C, glycerin-soaked wood pellets are prone to disintegration for all the settings except cool shot (low and high), where the air temperature was about 30°C and volume flow rate was about 9 L/s for low cool shot and about 12 L/s for high cool shot, respectively. Therefore, glycerin temperatures of 20°C and 30°C and cool shot options of drying were used to dry the glycerin-soaked wood pellets. Drying time reduces from 3 hours without dryer to 60 min with dryer at low cool shot and to 40 min at high cool shot option. This indicates that if faster drying is necessary, hair dryer could be used, but the cost of electricity should be kept in mind.

### Table II

<table>
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<tr>
<th>Method of detection</th>
<th>Species</th>
<th>Measured unit</th>
<th>Range</th>
<th>Resolution</th>
<th>Accuracy</th>
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<tr>
<td>NDIR</td>
<td>CO₂</td>
<td>%</td>
<td>0 - 20</td>
<td>0.1%</td>
<td>±1%</td>
</tr>
<tr>
<td>NDIR</td>
<td>HC</td>
<td>ppm</td>
<td>0 - 20,000</td>
<td>10 ppm</td>
<td>±1%</td>
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<td>Eletrochemical</td>
<td>CO</td>
<td>ppm</td>
<td>0 - 2000</td>
<td>1 ppm</td>
<td>±10 ppm &lt; 100 ppm, ± 5% of reading &gt; 100 ppm</td>
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<tr>
<td>Eletrochemical</td>
<td>O₂</td>
<td>%</td>
<td>0 - 25</td>
<td>0.1%</td>
<td>±1%</td>
</tr>
<tr>
<td>Eletrochemical</td>
<td>NO</td>
<td>ppm</td>
<td>0 - 5000</td>
<td>1 ppm</td>
<td>±1%</td>
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<tr>
<td>Eletrochemical</td>
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<td>ppm</td>
<td>0 - 800</td>
<td>1 ppm</td>
<td>±1%</td>
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Figure 7 shows the soaking result of Type C and Type D pellets. Here glycerin temperatures of 20˚C and 30˚C were considered, because temperatures higher than 30˚C disintegrated the glycerin-soaked pellets. High cool shot option of dryer was used to dry the pellet samples. It took about 25 min for the drying process for the pellet C and about 15 min for the pellet D. It is seen from Fig. 7 (a) that for Type C pellet, there is no change in soaking with time up to 10 min at temperatures of 20˚C and 30˚C. The rate of glycerin soaking at these conditions is 10%. The rate of soaking increased to 11%, which is only 1% increase for soaking time of 20 min for both temperature conditions. Figure 7 (b) shows that for Type D pellet, the rate of soaking (16-18% at 20˚C and 17-27% at 30˚C) is higher than Type C pellets. There is only 1% increase in soaking with temperature of 30˚C than that of 20˚C up to 10 min of soaking time, however, the rate of increase in soaking at 20 min soaking time is 9%.

B. Viscosity Test Result
Temperature plays an important role in soaking liquids into solids. Usually the higher the temperature, the higher the rate of soaking is. This phenomenon depends on many fluid properties, such as viscosity, surface tension, etc. This study investigated viscosity of crude glycerin at soaking temperatures of 20-70˚C. Figure 8 shows that the viscosity of crude glycerin at 20˚C is 110 cSt and it reduces to 15 cSt at 70˚C. These values are much lower than pure glycerin due to significant amount of moisture content (>20%) in crude glycerin. The higher temperature that causes lower viscosity helps to soak higher amount of crude glycerin because of less resistance to flow. Figures 5 and 6 show much higher soaking of crude glycerin at 60˚C than that at 20˚C. Lower surface tension force at higher temperatures also helps higher soaking at higher temperature conditions.

C. Pellets Fuel Institute Standard Test Result
At the proposed 5% rate of biodiesel use in diesel by 2015 in Canada, only 6% crude glycerin is required to mix with current production level of wood pellets. As the rate of soaking is much higher than the required rate at higher soaking times and temperatures, the samples considered for the PFI standard test were of 1 min soaking time and 20˚C soaking temperature. For this test and combustion test, Type A hardwood pellet was excluded, because it is a barbequing pellet which is much more costlier than heating pellets for industrial and residential use and it did not show any better characteristics for soaking and resistance to disintegration. Table 3 shows the PFI standard test results. It is found that all the pure wood pellets satisfy the PFI standard. However, glycerin-soaked Type B hardwood pellet and Type D softwood pellet did not satisfy the PFI standard for pellet durability index (PDI) (>95%) and amount of fines (<1%). PDI and fines for glycerin-soaked Type B hardwood pellet are 77.28 and 3.58%, and for glycerin-soaked Type D softwood pellet are 64.75 and 12.96%, respectively. The only glycerin-soaked pellet Type C softwood satisfies all the PFI standard test parameters including PDI and fines. All glycerin-soaked
wood pellets show lower chloride than that of pure wood pellets, because no choline is detected in crude glycerin.

Figure 9 shows a photograph of pure and glycerin-soaked wood pellets for 1 min soaking time and 20°C soaking temperature, when they are dried by high cool shot option of the drier. From the photograph, it may be suspected that glycerin-soaked Type D softwood pellet and Type B hardwood pellet might be more prone to disintegration. Fines test proved the suspicion and percentage of fines were 12.96% and 3.58%, respectively for glycerin-soaked Type D softwood pellet and Type B hardwood pellet.

Table 4 shows the ultimate and proximate analyses and higher heating value of different pellets and crude glycerin. All the glycerin-soaked pellets show increased HHV than pure pellets due to a slight increased HHV of crude glycerin than pure wood pellets. Furthermore, glycerin-soaked wood pellets show lower sulphur content than pure wood pellets due to no sulphur in crude glycerin.

**D. Emission Test Result**

Although the analyzers can measure CO, CO₂, O₂, NO, NO₂ and HC, no HC and NO₂ were detected. This means that the HC and NO₂ emissions from pellet combustion is less than 10 ppm and 1 ppm, respectively, because these are the minimum detectable limit of these emissions by the analyzer. From two thermocouples’ reading, the average temperature of the front panel is determined. The average front panel temperature of three readings was about 72°C for all pellet types except the Type C, which showed the average front panel temperature of about 78°C after 20 min of running. Almost constant front panel temperature and exhaust temperature indicate a steady test condition. Figure 10 shows emissions of CO, NOx and CO₂ of six types of wood pellets, three pure and three glycerin-soaked. It is seen from Fig. 10(a) that Type C wood pellet produces the least CO emissions both for pure and glycerin-soaked pellets. Type B and Type D pure wood pellets produce about 200 ppm and 150 ppm of CO, respectively, whereas the CO production with Type C pellet is about 100 ppm. However, much higher CO is produced with glycerin-

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**Table III**

<table>
<thead>
<tr>
<th>Fuel property</th>
<th>Type B (soaked)</th>
<th>Type B (pure)</th>
<th>Type C (soaked)</th>
<th>Type C (pure)</th>
<th>Type D (soaked)</th>
<th>Type D (pure)</th>
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<tr>
<td>Bulk density (kg/m³)</td>
<td>520.2</td>
<td>675.3</td>
<td>623.8</td>
<td>704.5</td>
<td>492.7</td>
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<td>Diameter (mm)</td>
<td>6.88</td>
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<td>6.79</td>
<td>6.57</td>
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<td>Pellet durability index (%)</td>
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<td>Fines (%)</td>
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<td>90</td>
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</table>
Type B wood pellet

Type B wood pellet (glycerin-soaked)

Type C wood pellet

Type C wood pellet (glycerin-soaked)

Type D wood pellet

Type D wood pellet (glycerin-soaked)

Fig. 9. Photograph of pure and glycerin-soaked wood pellets
soaked wood pellets combustion; it is 2.3-2.9 times higher than that of pure wood pellets. Figure 10(b) shows NOx emissions of different wood pellets combustion. It is to mention that as there was no NO2 detected, NOx (sum of NO and NO2) here indicates the NO emissions. It is found that glycerin-soaked wood pellets produce less NOx than pure wood pellets do. The NOx production of Type B, Type C and Type D wood pellets are 37 ppm, 36 ppm and 33 ppm, respectively. Glycerin-soaked wood pellets produce about 16-25% less NOx than that of pure wood pellets. Figure 10(c) shows emissions of CO2 from different wood pellets combustion. It is observed that glycerin-soaked wood pellets produce less CO2 than pure wood pellets combustion. The CO2 production of Type B, Type C and Type D wood pellets are 2.4%, 3% and 2.5%, respectively. Glycerin-soaked wood pellets produce 2-2.4% CO2, which is about 16-20% less than that of pure wood pellets.

Fig 11 shows the average exhaust gas temperatures for different wood pellets. Glycerin-soaked wood pellets show lower temperatures than that of pure wood pellets, and Type C wood pellet produces the highest exhaust gas temperatures both for pure and glycerin-soaked wood pellets. The least CO and the most CO2 production from the combustion of Type C wood pellet can be correlated with highest exhaust gas temperature, which is proportional to the highest combustion temperature for steady-state operation. This fact indicates that Type C

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**Table IV**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Pellets</th>
<th>Type B (soaked)</th>
<th>Type B (pure)</th>
<th>Type C (soaked)</th>
<th>Type C (pure)</th>
<th>Type D (soaked)</th>
<th>Type D (pure)</th>
<th>Crude glycerin</th>
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<td><strong>Ultimate analysis, db (%)</strong></td>
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<td>C</td>
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<td>46.936</td>
<td>46.513</td>
<td>53.721</td>
<td></td>
</tr>
<tr>
<td><strong>Proximate analysis, (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>6.99</td>
<td>4.96</td>
<td>7.86</td>
<td>6.09</td>
<td>7.47</td>
<td>6.34</td>
<td>21.31</td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>1.21</td>
<td>0.96</td>
<td>0.65</td>
<td>0.52</td>
<td>1.30</td>
<td>0.32</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>76.55</td>
<td>85.56</td>
<td>74.82</td>
<td>83.84</td>
<td>75.51</td>
<td>84.51</td>
<td>56.16</td>
<td></td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>16.33</td>
<td>8.520</td>
<td>16.68</td>
<td>9.55</td>
<td>15.73</td>
<td>8.83</td>
<td>20.05</td>
<td></td>
</tr>
</tbody>
</table>
wood pellet performs the best from the combustion point of view. Higher CO, lower CO₂ and lower exhaust gas temperatures from glycerin-soaked wood pellets’ combustion are an indicator that the combustion performance of these pellets is lesser than that of pure pellets.

If the moisture content of crude glycerin is looked at (Table 4), an explanation of lesser efficient combustion with glycerin-soaked wood pellets can be formulated. Crude glycerin has more than 20% moisture content, whereas the average moisture content of pure wood pellets is about 5.5%. Therefore, glycerin-soaked wood pellets have higher moisture content as seen in Table 4. It is known that pyrolysis is one pre-combustion stage of biomass combustion, which occurs at 250-300°C. The char takes part in primary combustion and the pyrolysis gases take part in secondary combustion. High moisture slows down combustion and cools down the gases produced by pyrolysis. This causes less efficient combustion locally and consequently higher CO is produced. Much higher CO production with glycerin-soaked wood pellets’ combustion support this explanation.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

This study examined an alternative use of crude glycerin from biodiesel production in Canadian wood pellet industry through different steps of fuel property and combustion analysis. The following are the conclusions drawn based on the experimental results.

1) Crude glycerin produced as a by-product of biodiesel production has a higher heating value than common wood pellets available in Canadian markets. This makes crude glycerin an option to consider mixing with wood pellets to produce value-added product for industrial and residential heating.

2) Glycerin soaking rate even in 1 min of soaking time and at soaking temperature of 20°C (room temperature) is more than 10% and it is increased significantly at higher soaking temperatures and time. However, higher rate of soaking makes wood pellets vulnerable to disintegration.

3) Among all glycerin-soaked pellets, only Type C softwood pellet satisfies the PFI standards of commercial/residential densified fuels. Therefore, this type of pellet producers can take the advantage of glycerin-soaking to increase their revenue.

4) The combustion performance of pure and glycerin-soaked Type C pellet is the best among all the pellet fuels. Glycerin-soaked pellets showed lower CO₂ and NOx emissions than that of pure wood pellets.

B. Recommendations

Observing the results and from our experience, the following investigations are recommended.

1) A controlled mixing of crude glycerin with sawdust to produce densified wood pellets in a pellet press can be considered. By this way, different sawdust (soft or hard wood) can be used to produce wood pellets, which might satisfy the PFI durability and fines requirements.

2) Additives, for example starch, etc. in addition to crude glycerin may be considered to give better durability of commercial/residential wood pellets.

3) Reduction of moisture content of crude glycerin by improving the biodiesel production technique without any additive heating and testing in industrial/residential stoves/furnaces to reexamine the combustion performance and emissions is recommended.

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REFERENCES


