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Testing the performance and compatibility of degummed soybean heating oil blends for use in residential furnaces

Teshome E. Jiru [a], Bradley G. Kaufman [a], Klein E. Ileleji [a,*], Daniel R. Ess [a], Harry G. Gibson [a], Dirk E. Maier [b]

[a] Agricultural and Biological Engineering Department, Purdue University, 225 South University Street, West Lafayette, IN 47907, United States
[b] Department of Grain Science and Industry, Kansas State University, 201 Shellenberger Hall, Manhattan, KS 66506, United States

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ABSTRACT

Degummed soybean heating oil (SHO) is a renewable energy resource, which can reduce dependence on foreign oil and create a new market for the soybean industry. This study demonstrated that SHO 20 (20% degummed soybean oil and 80% No. 2 fuel oil) is suitable for application in residential furnaces without modification. The tests conducted were: fuel properties, seal compatibility, long-term storage, and laboratory and field combustion. The physical property tests showed that the kinematic viscosity (0.0346 cm^2/s) and the pour point of SHO 20 (-30 °C) were within the ASTM requirement for No. 2 fuel oil; and the net heating value of SHO 20 (43.9 MJ/kg) was only 1–3% lower than the No. 2 fuel oil value (45.6 MJ/kg). Compatibility tests performed on the rubber seals and gasket materials (Nitrile and Viton) found in typical heating fuel pump systems indicated that the tensile strength and hardness values were not significantly affected by SHO blends when compared with No. 2 fuel oil. A long-term storage test revealed that there was no significant change in heat content and no visible stratification of SHO 20 blend during three months of storage. The pump pressure and the type of nozzle used affected the concentration of NO_x, SO_2, and CO in the flue gas. As was expected, increasing the SHO fraction in the blend also reduced the SO_2 emission. The combustion of SHO 20 resulted in a higher flue gas temperature which increased the NO_x emission than with No. 2 fuel oil.

1. Introduction

Biodiesel and ethanol have become important renewable energy resources in the United States as the demand and price for energy continues to increase. Soybean oil, as an additive to No. 2 fuel oil, makes an important contribution to the security and energy independence of the United States. Specifically, soybean heating oil (SHO) which has been slightly refined by degumming has the potential to decrease the nation's dependence on foreign oil. While biodiesel, lipids which have been converted to methyl esters by transesterification is the most widely commercial use of vegetable oils as a fuel, using unrefined or slightly refined vegetable oils have been suggested for use since the discovery of compression ignition engine by Rudolph Diesel in 1897. Vegetable oils are used primarily in food or other edible consumables. Its large scale use as a fuel is only a recent development, and this application has raised some doubts, most especially because of the impact it might have on food prices.

No. 2 fuel oil is considered a middle distillate fuel related to diesel and kerosene fuels. In 2001, the United States used a total of 6.6 billion gallons of No. 2 fuel oil in residential heating applications and the northeast region was by far the largest consumer with nearly 5.8 billion gallons [1]. If one quarter of the total northeast consumption was replaced with a 20% soybean heating oil blend, 290 million gallons of soybean oil would be required. This would represent about 10% of the 3 billion gallons of soybean oil produced in 2002, or about 8% of the 72 million acres of soybean production, which indicates the tremendous impact on the agricultural and oil production industries if SHO were commercialized.

Biofuels have been marketed to consumers in an attempt to increase conversions in new home installations and SHO has great potential to assist the oil heat industry meet goals recently adopted in the industry roadmap [2]. According to the National Oil heat Research Alliance (NORA), residential heating oil provides consumers with dependable and better quality heat compared to natural gas or electric heat. Hence, any modification to the current heating oil supply should maintain, if not improve, the current image presented by NORA and its member companies.

The physical and chemical properties of fuel such as pour point, cloud point, flash point, heat of combustion, viscosity, and composition are important for efficient storage, transport, and fuel consumption. Pour and cloud points are cold weather fuel properties that are important primarily in outdoor storage and during

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* Corresponding author. Tel.: +1 765 494 1198; fax: +1 765 496 1115.
E-mail address: ileleji@purdue.edu (K.E. Ileleji).

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transportation. Fuel delivery lines, especially in residences with outdoor storage tanks, are very susceptible to cold weather problems due to their small diameter. The cold weather makes the fuel unable to flow and wax crystals may settle to the tank bottom or clog filters, nozzles or strainers during operation. The heat of combustion of the fuel is very important because fuel oil is used in hot water and forced air-heating systems for space heating applications. When economic and emissions factors are equal, the fuel with the highest heat energy content is the most valuable. High-energy fuels can produce more heat per dollar and emission unit than lower heat content fuels. Viscosity is important for pumping of the fuel oil and the atomization process in the burner. The higher the degree of saturation of oil, the more viscous the oil becomes [3].

A stable fuel with consistent quality is essential for reliable and efficient operation of heating systems [4]. Crude vegetable oils can be stored in large tanks with minimal oxidative degradation if they are kept clean, cool, dry, and access to air is limited [5,6]. Heating oil tends to degrade with time and storage as it goes through a natural aging process. Long-term storage stability studies on biodiesel (B100, methyl esters) and biodiesel blends showed that biodiesel formed more sediment than the petroleum diesel fuel although the actual quantity was relatively small [7]. Further analysis of long-term storage stability of petroleum diesel fuel, SHO 10, SHO 50, and 100% degummed soybean oil over a period of 16 months indicated no stratification in any of the blends except evidence of sediment deposit in the higher percentage blends, which could potentially be a problem for residential tanks and lead to plugging of filters, strainers, and nozzles [6]. Also, the addition of diesel fuel in 1:1 ratio could improve the stability of the crude and degummed vegetable oils more than the stability of the more refined oils [8]. This indicates that the stability of soybean oils decreases with an increase in the amount of refining. However, blending unstable and stable middle distillate fuels with soybean-derived oil in concentrations up to 20% improved the stability of both the stable and unstable middle distillates [9].

Bessee and Fey [10] conducted a study on the compatibility of elastomers and metallic components commonly found in fuel systems with B20 and B30 biodiesel fuel blends. Physical properties such as tensile strength, elongation, hardness, and swelling were determined after completion of the test. The physical properties of nitrile rubber, nylon, and high-density polypropylene were affected the most by the biodiesel blends. The copper-containing metals exhibited severe corrosion when exposed to the biodiesel blends and formed large amounts of gum. The steel and aluminum did not form gum but had high total acid numbers, which could lead to corrosion. Although more research was recommended, the study indicated that Teflon and Viton materials are a possible solution to elastomer compatibility problems. No previous tests have been conducted on the compatibility of SHO with seals and containers.

Fuels subjected to combustion emit carbon monoxide (CO) and carbon dioxide (CO_2), nitrogen oxide (NO_x), sulfur dioxide (SO_2), and sulfur trioxide (SO_3). CO_2 and CO emissions change proportionately with the carbon in the fuel and by the amount of oxygen present during combustion. Optimum combustion produces minimal CO and maximum CO_2 values. This improves combustion efficiency because CO absorbs heat and results in higher flue gas losses.

The oil heat industry roadmap lists NO_x emissions as a major concern in the competition between heating oil and other fuels [2]. The ability of emissions to function as a catalyst in the chain reaction formation of ozone and carbonyl groups is the primary concern [11]. Nitrogen oxide (NO_x) pollutant emissions category consists of two compounds: nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the primary contributor and NO_2 contributes very little to the total emissions.

All petroleum oil contains varying amounts of sulfur upon extraction from the earth. The refiner, in order to comply with local laws and regulations, adjusts the final sulfur content. Soybean oil has virtually zero sulfur content. Both sulfur dioxide (SO_2) and sulfur trioxide (SO_3) are combustion by-products due to fuel-bound sulfur. In general, a positive linear relationship was found between the fuel sulfur content and SO_2 emissions [12].

The main objective of this study was to evaluate the performance of different blends of degummed soy heating oil (SHO) blended with No. 2 fuel oil for residential heating applications. Tests conducted on SHO blends included physical and chemical property, seal compatibility, long-term storage, and laboratory and field combustion. To this end, the materials and methods employed, the results obtained and the conclusions drawn from this study are discussed in the subsequent sections.

2. Materials and methods

Four types of tests were conducted on SHO: fuel properties, long-term storage (three months), seal compatibility, and combustion tests. Blend ratios from No. 2 fuel oil to pure soybean oil were analyzed for characteristics beneficial to residential heating applications. Soybean heating oil blends for this project were mixed using a splash blending technique. This method involved pouring the denser soybean heating oil into a container, which initially held only the No. 2 fuel oil. No special chemicals or additives were used to maintain the mixtures.

2.1. Fuel property test

Pure degummed soybean heating oil, SHO 20, and SHO 50 were submitted for analysis to an off-site analytical lab. SHO *XX* indicates the percent by volume of SHO blended with No. 2 fuel oil. Seven separate ASTM methods were employed to determine flash point: ASTM D93, pour point: ASTM D 97, cold filter plugging point: ASTM D 6371, cloud point: ASTM D 2500, kinematic viscosity: ASTM D 445 and elemental composition: ASTM D 2622 and ASTM 5291 for each sample. The sample viscosity was determined at 37.8 °C. Heat of combustion tests were performed in the Agricultural and Biological Engineering Department laboratory at Purdue using an adiabatic oxygen bomb calorimeter (Parr 1241, Parr Instrument Company, Moline, IL). The test was conducted based on ASTM 4809, which provides the test method for heat of combustion of liquid hydrocarbon fuels by a bomb calorimeter.

2.2. Long-term storage test

Five fuel blends were used to conduct long-term storage: No. 2 fuel oil, SHO 10, SHO 20, SHO 50, and SHO 100. The samples were placed into three different types of containers: 900 ml brown reagent glass (used as a control), 500 ml HDPE plastic bottles, and 3000 ml steel paint cans (to represents storage in standard residential tanks). The samples were stored in three different locations with different temperature ranges: explosion proof cabinet (indoor storage), explosion proof refrigerator at 8 °C and outside at varying outdoor temperatures away from direct sunlight and from precipitation. The outdoor location was of most interest due to diurnal fluctuation in temperature and humidity. The samples were visually inspected for any buildup or deposits. All samples were stored for a period of three months. After storage, the samples were also analyzed for heat energy content changes using an adiabatic oxygen bomb calorimeter (Parr 1241, Parr Instrument Company, Moline, IL).

2.3. Seal compatibility test

The two elastomer materials used in the seal compatibility tests were Nitrile and Viton. Nitrile is a material used for all of the current fuel pump drive shaft seals and Viton is a material that was shown to be resistant to biofuels by other researchers [10]. Samples of the two materials were placed into four different fuels: No. 2 fuel oil, SHO 20, SHO 50, and pure degummed soybean oil (SHO 100). The test was conducted according to ASTM D 471 which involved soaking of the rubber elastomers in each of the designated fuels for 1000 h. ASTM standards D 412 and D 1415 were employed for the tension and compression testing of the elastomers after they were soaked for the recommended period of time.

The tension test samples were cut into rectangular specimens with dimensions 5.08 cm by 2.54 cm by 0.16 cm. The compression test samples were cut into rectangular specimens with dimensions of 5.08 cm by 2.54 cm by .64 cm. Three samples of each material were placed in individual 375 ml steel containers filled with the designated test fuels. The samples were completely submerged in the fuels and were placed in a heating box that was controlled by the oil-fired furnace in the laboratory at Purdue University. The temperature inside the box was controlled between 35 °C and 51.7 °C using a thermostat. These temperatures are in the ranges specified in ASTM D 471. The samples were subjected to this heating pattern for a total of 1000 h as recommended by ASTM D 471. After completion of the test, the samples were removed from the box and observed for any visual changes in appearance.

The tension tests were performed using a Sintech testing machine (MTS, Eden Prairie, MN). The test setup consisted of two sets of grips that were used to stretch the sample. The machine was set up to produce a uniform rate of grip separation of 500 ± 50 mm/min. The specimens were placed in the separation grips and extended at a constant rate until rupture. The tensile strength and percent strain at break were measured. Constant width and thickness values were determined for each sample by averaging a set of ten samples. The distance between the grips was measured for each individual sample immediately before applying the load. A statistical analysis was performed on the tensile strength and percent strain at break tests to determine if there was any difference between the sample means. A sample mean was calculated based on the 3 samples for each material and fuel combination. A student's test was used at a 0.05 significance level for both the tensile strength and percent strain comparisons. The standard error of the difference between two sample means was used for a comparison between the control and fuel samples.

The compression tests were also done using the Sintech testing machine (MTS, Eden Prairie, MN). The test setup consisted of a vertical plunger, which terminated into a rigid ball with diameter of 2.50 ± 0.01 mm. An increasing force was applied to the sample until it reached a peak load of 8.3 ± 1.5 N. The depth of penetration of the ball was recorded at three different locations for each sample and the mean value of the locations was used to determine the International Rubber Hardness Degrees (IRHD). The IRHD test is intended to provide an indication of the elastic modulus of the material being tested on a scale of 0 to 100. A value of 0 indicates a material with zero elastic modulus while a value of 100 represents a material with an infinite elastic modulus. One IRHD is equal to 0.4 mm of penetration. A statistical analysis was performed on the compression tests to determine if there was any difference between the sample means. A set of nine sample values was used to determine the sample mean for each material and fuel combination. A comparison was conducted using the standard error of the difference between two sample means, between the control and samples soaked in fuel.

2.4. Laboratory combustion test

A Thermo Pride forced air boiler (CHB68-112B, Thermo Products, North Judson, IN) shown in Fig. 1 was employed for the combustion test. The design has the heat exchanger stacked on the combustion chamber with flue and warm air outlets on top. The specification plate recommended 13% CO_2 flue gas concentration with a maximum temperature rise of 21 °C for optimal furnace operation.

2.4.1. Burner and control unit

A Beckett AF (EFL101, Beckett Corporation, Elyria, Ohio) burner unit was used until July 2004. In July 2004, a Beckett AFG model was installed to allow for a more complete set of emission results using a more efficient burner. The burner unit controlled the fuel flow, combustion airflow, and flame ignition. It contained electronic controls, a gear type fuel pump, a combustion air blower, and an excess air control. The fuel pump was rated to operate

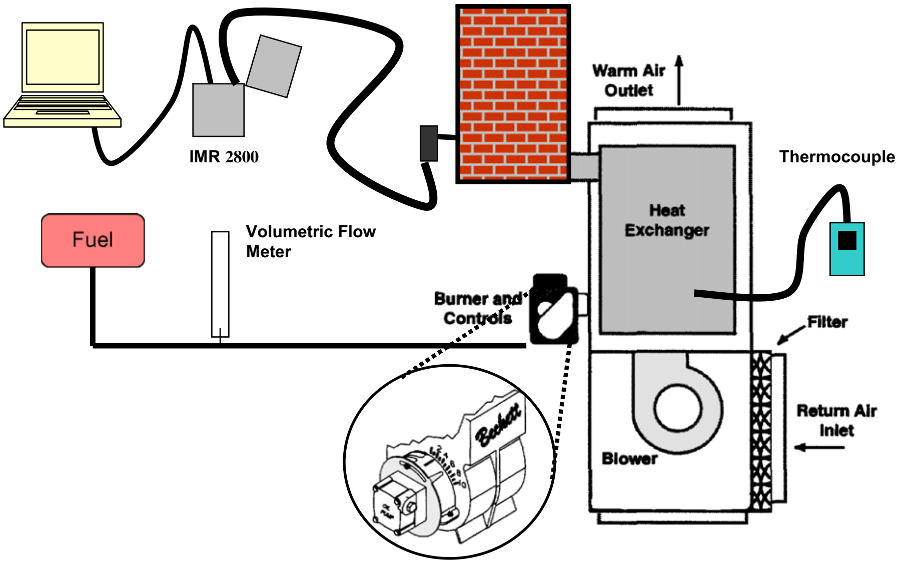

Fig. 1. Laboratory combustion test set up.

between 100 and 200 psi. The burner was rated for 130 psi for use with the boiler. The pump pressure was easily adjusted by using an Allen wrench and pressure gauge. The air shutter setting had great effect on the quality of combustion and furnace efficiency. The main function of the shutter control was to minimize excess air and, therefore, increase the overall efficiency both in the boiler and furnace. The air shutter had an arbitrary number scale ranging from zero to ten. A zero setting means no excess air is available for the combustion process. Here, combustion air is still available to the combustion process, although it is not enough to produce efficient combustion. The amount of excess air available changes the O_2 and CO_2 levels in the flue gas, which are important indicators of excess air and furnace efficiency.

2.4.2. Nozzles

The furnace manufacturer recommended four nozzle types: 0.60 × 80°, 0.75 × 80°, 0.85 × 80°, and 1.00 × 80°. The first figures are the fuel flow rates in gallons per hour (GPH) and the second ones are the spray angles. For example, the first nozzle has a fuel flow rate of 0.60 GPH (631 mm^3/s) and spray angle of 80°. All four nozzles are hollow cone nozzles, which atomize and spray the fuel with a hollow cone pattern. These type of nozzles are commonly used in small burners with fuel flow rates less than 1051.5 mm^3/s rated at 690 kPa and have more stable spray angles under adverse conditions compared to solid cone nozzles at the same flow rate [13]. Increasing or decreasing the spray angle may cause the fuel droplets to collide with the chamber walls and reduce combustion efficiency. The theoretical heating capacity for the furnace and nozzle was calculated using the nozzle flow rate and the fuel heating value.

2.4.3. Combustion gas analyzer and thermocouples

An IMR® 2800 instrument (IMR Environmental Equipment, St. Petersburg, FL) was used to measure the flue gas composition and temperature. This analyzer was designed for portability and fast and efficient setup. A three-minute self-calibration was required before data collection. The "light fuel oil" setting was used which was related to other fuels such as fuel oil numbers 1 and 2, kerosene, and jet fuel. The detection probe measures flue gas temperature with a thermocouple and allows flow of gas to the analyzer. A built-in sampling pump drew the flue gas through a condensation trap and a particle filter and then into the sensor chamber.

2.4.4. Flow rate measurement

A 50-ml burette and stopwatch were used to measure the volumetric flow rate of fuel. The burette was in-line with the fuel delivery system between the filter and the burner pump. During flow rate measurements, a valve at the filter was closed and the burette stopcock was fully opened. The stopwatch was used to measure the time required for the furnace to consume a specified volume, typically greater than 10 ml. Flow rates for No. 2 fuel oil, SHO 20, and SHO 50 blends were measured to analyze the performance of the system.

2.4.5. Smoke gun

A Bacharach smoke gun (Bacharach Inc., New Kensington, PA) was used to obtain the "smoke spot number" from the flue exhaust. The operation is similar to a bicycle tire pump except that this device pulls a vacuum instead of pumping air. ASTM standards D 2156-94 and D 2157-94 were employed in this data collection procedure. A 15-min furnace warm-up period was recommended before data collection began. A minimum of four air shutter settings with operating times of four minutes apiece are recommended for smoke spot determination. The resulting spot was then compared to a standard chart with color ratings from 0 to 9. A zero is best in terms of low to no smoke production while a 9 is an indication of poor combustion quality.

2.4.6. Test procedure

Degummed soybean oil was blended with No. 2 fuel oil to create fuel mixtures of 20% and 50% by volume, SHO 20 and SHO 50, respectively. The splash blending method dumped degummed soybean oil through No. 2 fuel oil in order to properly mix the blend. The SHO 50 was selected as the upper limit after preliminary tests showed difficulty with flame ignition during cold starts in blends above this value.

Steady state combustion emissions were collected for 27 different controlled operating conditions. The fuel, nozzle, and pump pressure combination was held constant while the air shutter value was varied. Table 1 lists the different furnace system settings used during laboratory combustion tests.

At least two separate laboratory tests for each fuel and nozzle configuration were performed on different days. One test, for example, used SHO 20 with a 0.60 × 80° nozzle. For this test, the system pressure was changed to one of the three pressures listed. The air shutter value was adjusted to 4–5 positions and the furnace was allowed to reach steady state. This resulted in over 12 steady state data sets for the fuel and nozzle combination. The time required for the system to reach steady state was 5–10 min. Steady state was determined using both emissions and temperature data. The furnace was considered to be at steady state when the O_2, NO_x, and SO_2 emissions stabilized and the flame temperature remained constant. Average steady state values were determined for all emissions; smoke spot number, and temperatures by using the flue oxygen percentage reading. The average volumetric fuel flow rate was determined independently of the flue oxygen percentage. All flow rate readings for each nozzle type, pump pressure, and fuel combinations were averaged.

3. Results and discussion

3.1. Fuel property test

Table 2 lists results of fuel chemical and physical property tests. The cloud, pour, and filter plugging temperature points all increased with an increase in the degummed soybean oil content. This general trend agreed with biodiesel blends and the flash points for the soybean heating oil blends agreed with published data for biodiesel heating oil blends, which showed a nearly constant flash point up to a B30 blend, and increased up to pure biodiesel [14]. The test results showed that the flash points for SHO 20 and SHO 50 blends were 71 °C and 73 °C, respectively, and were within the range of values for No. 2 fuel oil, 54.4 °C and 101.1 °C [15,16]. The flash point for pure degummed soybean oil was 185 °C, which is considerably lower than 328 °C reported by Snyder and Kwon [17]. Snyder and Kwon [17] did not mention the method they used to determine the value so it was difficult to compare our values directly.

Table 1

Nozzle types, pump operating pressures, and excess air setting for heating fuel types used for laboratory combustion tests.

Fuel type	Pump pressure (kPa)	Nozzle type[a]	Air shutter setting
No. 2 fuel oil	690	0.60 × 80°	0–10
SHO 20	896	0.75 × 80°	0–10
SHO 50	1103	0.85 × 80°	0–10

[a] Nozzle type identifier by manufacturer – first figures are the fuel flow rates in gallons per hour (GPH) and the second ones are the spray angles.

Table 2
Results of the physical and chemical properties tests.

	SHO 100	SHO 20	SHO 50	No. 2 fuel oil
Cloud point (°C)	−7.0	−27	−20.0	−12.8
Pour point (°C)	−9.0	−30	−24.0	−29
Cold filter plugging point (°C)	10.0	−32.5	−23.5	−34
Flash point (°C)	185	71	73	68
Kinematic viscosity at 37.8 °C (cm^2/s)	0.332	0.0346	0.079	2.09
Sulfur ppm (weight)	<10	215.5	117.5	277
Ash content% (weight)	<0.005	<0.005	<0.005	
Carbon% (weight)	78	85	79.93	
Hydrogen% (weight)	12.94	12.54	11.56	
Nitrogen% (weight)	0.09	0.08	0.055	
Oxygen% (weight)	1.91	3.74	8.47	

Vegetable oils have higher viscosity than No. 2 fuel oil. Hence, the viscosity of SHO blend increased as the blend ratio of SHO with No. 2 fuel oil increased. It can be observed from Table 2 that the kinematic viscosities of SHO 20 and SHO 50 were 90% and 76%, respectively, lower than the kinematic viscosity of SHO 100. The kinematic viscosity of SHO 20 was 57% lower than that of SHO 50. The kinematic viscosity of the SHO 20 blend was 0.0346 cm^2/s, which is within the ASTM recommendation for No. 2 fuel oil.

The composition analysis results in Table 2 were reported on a weight basis with sulfur content values in parts per million and all others as percentages. Carbon and hydrogen shared the majority of the composition of the blend, which was expected for hydrocarbons. The carbon content decreased as the amount soybean oil content in the blend increased from SHO 20 (85%) to SHO 100 (78%). Feldman et al. [18] measured an 8% decrease in carbon content from B20 to B100. Nitrogen and sulfur, both contributors to combustion emissions, were shown to decrease in percentages with an increase in soybean oil content. This was expected since vegetable oils have no or negligible sulphur content making them favorable for reducing SO_x emissions. Sulfur decreased from 215.5 ppm with SHO 20 blends to less than 10 ppm with SHO 100. The sulfur content for No. 2 fuel oil was 277 ppm, indicating that the fuel oil is low sulfur type. The nitrogen contents increased from 0.08% for the SHO 20 blend to 0.09% for SHO 100. The analysis showed the oxygen level in SHO 100 was 1.91% by weight.

The net heating values for pure components as well as the primary blends of soybean heating oil are listed in Table 3. Pure samples of soybean oils showed an 11–14% (by weight) or 7–10% (by volume) decrease in net heating value when compared to No. 2 fuel oil. When SHO 20 and soy methyl ester blends were considered, the net heating value showed only a 1–3% decline on a volume basis. SHO 50 showed a 3.5–6% decrease in the net heating value on a volume basis.

3.2. Long-term storage test

For the long-term storage test (three months), three containers types and three storage conditions (a total of 45 samples) were used. Visual observations made for every fuel sample in the storage test are summarized in Table 4. No noticeable changes were observed in any of the SHO 20 samples and were not included in the table. There was no stratification of the two oils in any of the blends and storage conditions. However, there was evidence of deposits in the majority of the oils. Flakes were typically white in color and readily moved with agitation. Some black spots about the size of a thumb tack were also noted. Film deposits in SHO 100 were found in six of the nine containers. The other three showed cake deposits of which two were from outdoors. The only five fuel samples to contain flakes were SHO 10 blends. The flakes were present across all three container types and storage conditions. Thin films were noted on all other samples. The SHO 50 blend stored outdoors in plastic had cake and dirt. All three refrigerated samples and two room temperature samples had either cake or film at the bottom of their containers. This could be residual hydratable phospholipids left over from the degumming process. No analysis was performed on the deposits so the actual composition was not determined. Overall, 15 fuel samples, primarily SHO 50 and SHO 100, showed signs of film and sediment deposits. The deposits could potentially be a major issue for high percentage SHO blends in residential tanks. They could contribute to sludge formations at the bottom of residential fuel oil storage tanks over time. The majority of No. 2 fuel oil samples showed little visual affects during long-term storage.

The results of heat of combustion tests showed little difference in heat content values between the initial standards values in Table 3 and values obtained after the long-term storage test. There were only 7 samples that were not included in the 95% confidence intervals based on the standard deviations of the mean standard values. These values could be outside the 95% interval due to procedural errors in running the bomb calorimeter. The test result indicated that the effects of long-term storage on heat content seem to be insignificant because all of the values are within two standard deviations of the mean for each blend. The results also confirmed that increasing the percentage soybean oil, decreased the heat content as was expected. The standard value for No. 2 fuel oil was 45.6 MJ/kg and for SHO 100 was 39.5 MJ/kg. The heat content of SHO 20 was 43.9 MJ/kg, which is between the values of No. 2 fuel oil and SHO 100.

Table 3
Heat content of SHO blends.

Fuel[a]	Volume basis (MJ/L)	Mass basis (MJ/kg)
No. 2 fuel oil	38.8	45.6
SHO 20 (degummed)	37.8	43.9
SHO 50 (degummed)	36.9	42.2
Degummed soybean oil	35.6	39.5
Crude soybean oil	36.0	39.5
Soy methyl esters	34.9	40.4

[a] Five tests were performed for each degummed soybean heating oil blend while two tests per blend were used for the other oils.

3.3. Seal compatibility test

A comparison of the tensile strength properties for both Nitrile and Viton elastomers is shown in Fig. 2. The results indicated that Viton did not seem to be affected by any of the fuels when compared to the control samples over a period of 1000 h. This result was expected, based on previous research [10] and demonstrated the good resistant properties of Viton. The results for Nitrile showed a difference in tensile strength when compared to the control samples. A 52% reduction was observed in the No. 2 fuel oil

Table 4
Long-term storage tests (three months of storage).

Fuel	Container type	Storage location[a]	Film	Cake	Water	Flakes	Spot	Dirt
No. 2 fuel oil	Plastic	R, O, C						
	Glass	R	x					
	Glass	C, O						
	Steel	O				x		
	Steel	C, R						
SHO 10	Plastic	C, R				x		
	Plastic	O			x			
	Glass	O	x					
	Glass	R, C				x		
	Steel	C, R	x					
	Steel	O				x	x	
SHO 50	Plastic	R		x				
	Plastic	C						
	Plastic	O		x				x
	Glass	R, C	x					
	Glass	O						
	Steel	R, C	x					
	Steel	O						
SHO 100	Plastic	O, C, R	x					
	Glass	C	x					
	Glass	R, O		x				
	Steel	R	x				x	
	Steel	C	x					
	Steel	O		x				

[x] Indicates the occurrence of an observation such as film, cake, water, flakes, spot, and dirt.
[a] R = refrigerator, O = outdoors, C = cabinet.

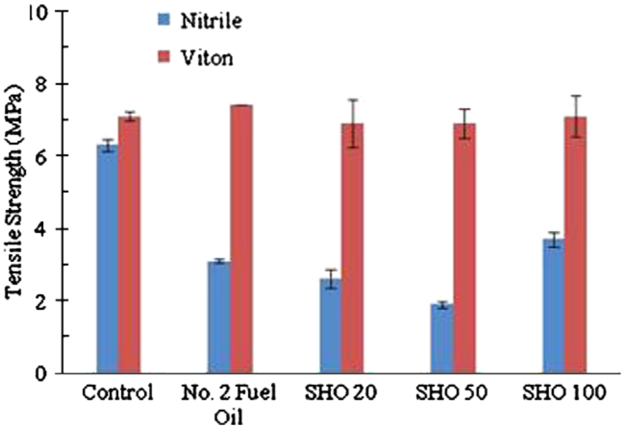

Fig. 2. Tensile strength comparison for Nitrile and Viton.

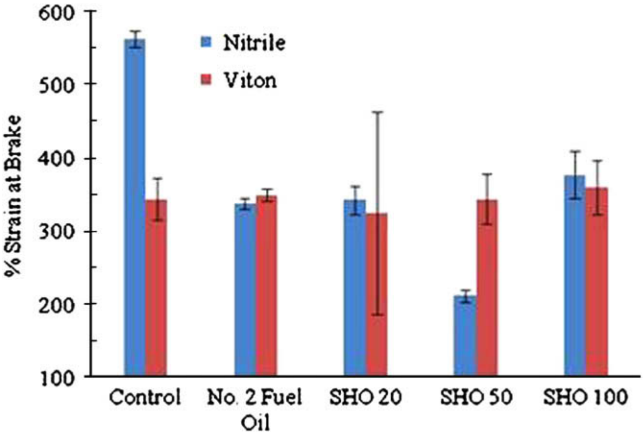

Fig. 3. Strain rate comparison for Nitrile and Viton.

sample. The SHO 50 samples had the highest percent change (70%) compared to the control samples. The significant reductions in tensile strength between the control and the samples placed in the No. 2 fuel oil and the SHO blends confirm a previous study [10]. The only statistically significant difference (using a *t*-test at a 0.05 significance level) was found between the No. 2 fuel oil and SHO 50 samples (a 39% reduction in tensile strength). The tensile strength of Nitrile decreased as the amount of SHO in the blend increased from zero (No. 2 fuel oil) to 50%. However, the SHO 100 sample showed an increase in tensile strength compared to No. 2 fuel oil. Further analysis may be required to determine the cause for this unexpected increase.

Fig. 3 depicts a comparison of the percent strain at break between Nitrile and Viton after a soak period of 1000 h. The results for the percent strain at break calculations were quite similar to those found for the tensile strength tests. The Viton samples did not appear to be affected by any of the fuels. However, the Nitrile samples showed a large difference between the control and soaked samples. The SHO 50 samples showed a large difference compared to the No. 2 fuel oil sample. Fig. 4 shows the compression test results expressed in units of International Rubber Hardness Degrees (IRHD). The results from the compression tests were similar to those found by the tension tests. The Viton appeared to be unaffected as there was little difference between the control samples and the samples soaked in the fuels. Again, there was a large difference in the compression properties of the control and the Nitrile samples exposed to the fuel. About 39% and 37% reductions were found between the control samples and the No. 2 fuel oil samples and SHO 20 samples, respectively. However, no noticeable differences in the compression properties of Viton for the No. 2 fuel oil and SHO blends were observed.

3.4. Laboratory combustion test

The primary goal was to demonstrate the need to adjust the air setting whenever a change was made to a furnace/boiler setup. The fuel flow rates were averaged from all measurements recorded for

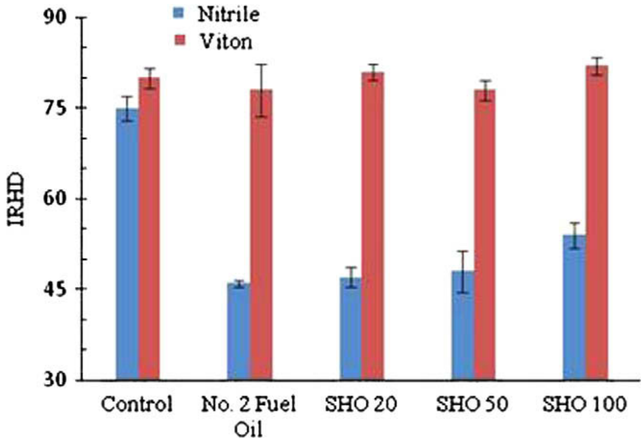

Fig. 4. Hardness comparison for Nitrile and Viton.

each furnace setting. The potential heat capacity for each nozzle and fuel were calculated using net heating values and the average flow rates.

3.4.1. Single furnace setup with all fuels

Table 5 summarizes emissions and excess oxygen at 1103 KPa and air shutter setting at 5. A combination of the air shutter setting of "5" and pump pressure of 1103 kPa was used because of the reasonably good combustion characteristics observed at this setting for all fuel and nozzle combinations. The high flow rate nozzles created a fuel-rich environment that required more oxygen to properly burn the fuel. This reduced the relative availability of oxygen in the combustion chamber and reduced excess oxygen in the flue gas. As listed in Table 5, all fuels showed a decrease in excess O_2 in the flue gas with an increase in nozzle flow rate. Table 5 also shows a general decrease in excess O_2 in the flue gas as the amount of SHO in the blend increased from zero (No. 2 fuel oil) to 50% except when 0.75 × 80° nozzle was used. The low flow rate nozzle, (0.60 × 80°), showed the lowest CO emissions among all fuel types. This was likely due to the availability of excess oxygen at this low flow rate, which increased fuel combustion. The higher flow rate, (0.75 × 80°) and (0.85 × 80°) nozzles delivered more fuel than required for combustion, increasing the demand for oxygen and resulting in poor combustion characteristics and higher CO concentration in the flue gas. Moreover, the increase in viscosity as the amount of SHO increased in the blend also affected fuel atomization of the blends by increasing the droplet size and decreasing the surface area required for complete combustion. Differences in carbon content in the fuel blends (Table 2) did not seem to contribute to the differences in CO composition of the flue gas. If this was the case SHO 20 should have higher CO in the flue gas than the other blends. This indicated that the conditions during the combustion process were more important than the elemental composition of the blends. Additionally, comparing excess O_2 and CO, it can be observed that for each blend and nozzle combination (except 0.75 × 80° and SHO 50), the higher the percentage of excess O_2 resulted in a reduction in CO in the flue gas.

There was a general increase in NO_x emissions with nozzle flow rate. Burning fuel at higher rates increased the temperature in the combustion chamber. From Table 6 it can be observed that the combustion of SHO 50 mostly results in a higher flue gas temperature than SHO 20 and No. 2 fuel oil. This increased the probability of thermal NO_x formation. A slight upward trend in NO_x emissions was also apparent from No. 2 fuel oil to the SHO 50 blends. This was likely attributed to higher flame temperatures in the SHO 50 blend. Comparison of excess $O_2$and NO_x showed that for each blend and nozzle combination, the higher the percentage of excess O_2, the lower the NO_x in the flue gas. This indicates that NO_x formation for all the tested blends was due to high temperature than the availability of excess oxygen.

Table 5 also shows that nozzle and fuel type also affected the SO_2 emissions. Both No. 2 fuel oil and SHO 20 showed decreases in emissions from the low to high flow rate nozzles. Even when operating at low excess air and poor combustion conditions, the SHO 50 blend produced virtually zero SO_2 emissions. This was likely due to the low sulfur content of the blend, thus increasing levels of SHO in the blend was expected to reduce SO_2 emissions. The changes in SO_2 concentrations in the flue gas for any of the blends as the nozzles were changed shows the importance of controlling conditions during the combustion process. The highest excess O_2 in the flue gas occurred when the nozzle (0.60 × 80°) with lowest flow rate was used. Comparison of excess $O_2$and SO_2 shows that for each blend and nozzle combination (except 0.75 × 80° and No. 2 fuel oil), the higher the percentage of excess O_2, the higher the SO_2 in the flue gas. This indicates that SO_2 formation for all the tested blends could be due to the combination of availability of excess oxygen and sulfur in the blend coming primarily from

Table 5
Emissions at 1103 KPa and air shutter setting at 5.

Nozzle type	No. 2 fuel oil	SHO 20	SHO 50
Excess O_2 (%)			
0.60 × 80°	9.10	8.41	6.71
0.75 × 80°	3.44	5.00	3.60
0.85 × 80°	2.61	1.78	1.69
CO (ppm)			
0.60 × 80°	10.51	11.26	13.86
0.75 × 80°	31.75	21.56	51.98
0.85 × 80°	30.85	43.02	26.90
NO_x (ppm)			
0.60 × 80°	60.07	66.17	90.55
0.75 × 80°	105.49	110.85	134.51
0.85 × 80°	128.23	121.88	160.90
SO_2 (ppm)			
0.60 × 80°	2.8158	7.3603	0.45911
0.75 × 80°	9.0299	2.871	0.1496
0.85 × 80°	2.3139	0.72532	0.00

Table 6
Emissions for the 0.60 × 80° nozzle at three pump pressures.

Pump pressure (kPa)	No. 2 fuel oil	SHO 20	SHO 50
NO_x (ppm)			
690	67.49	78.38	96.77
896	73.96	85.53	129.79
1103	87.57	93.02	130.81
SO_2 (ppm)			
690	0.20	8.41	0.20
896	3.36	6.12	0.14
1103	1.25	2.59	0.09
Temperature (°C)			
690	206.78	213.75	219.27
896	226.36	228.10	224.90
1103	229.96	236.64	244.77
Flow rate (mm^3/s)			
690	594.84	624.90	697.00
896	654.94	691.00	769.10
1103	690.98	739.06	835.20
Potential heating capacity (KW)			
690	22.92	24.02	25.91
896	25.12	26.22	28.73
1103	26.85	28.11	31.20

the No. 2 fuel oil. Further analysis over a wider range of air shutter settings may be needed to establish a trend in SO_2 emissions.

3.4.2. Emissions for other furnace settings

Table 6 lists emissions for the 0.60 × 80° nozzle at three pump pressures. The NO_x emissions showed a general increase with pressure. A difference in emissions between No. 2 fuel oil and SHO 20 could not be established when the analyzer's accuracy of 20 ppm was considered. The measured NO_x emission from SHO 50 was significantly higher at 95% confidence interval compared to SHO 20 and No. 2 fuel oil. The average SO_2 emissions showed a general decrease with increased fuel pump pressure for the three fuels. SHO 50 produced virtually zero SO_2 emissions. When the instrument accuracy of 20 ppm was considered, there was no significant difference between emissions from the three fuels.

Table 6 also presents the net flue gas temperature for the No. 2 fuel oil, SHO 20 and SHO 50 using the 0.60 × 80° nozzle. There was a general increase in the flue gas temperature with pressure. The temperatures of the flue gas produced from the three fuels were within 15 °C of each other for a given pressure setting.

Similar trends for NO_x and SO_2 emissions and temperature were observed for the other nozzles: 0.75 × 0.80° and 0.85 × 0.80° nozzles as pressure increased from 689.48 kPa to 1103.16 kPa. Comparison of emissions and net flue gas temperatures across nozzle types showed that the average NO_x emissions and net flue gas temperatures tended to decrease with lower fuel flow rates. For SHO 20 at 896.32 kPa, the 0.85 × 80° nozzle produced NO_x emissions of 115 ppm with a flue gas temperature of 305 °C. Using the same fuel and pressure, the 0.60 × 80° nozzle produced NO_x emissions of 85 ppm and 228 °C. SO_2 emissions for all fuel and nozzle types were less than 20 ppm. As stated above, the instrument could not accurately distinguish between the different SO_2 values when the values were less than 20 ppm.

3.4.3. Fuel flow rate and potential heating capacity

The volumetric fuel flow rate was measured for all furnace settings. The flow rate for each nozzle and fuel combination was found to be unaffected by the air shutter settings. As expected a general upward trend for all samples was noted with an increase in pump pressure. Table 6 shows flow rate increased with increase in fuel viscosity for 0.60 × 80° nozzle. SHO 50 has higher flow rates at the 95% confidence interval for all furnace settings. Other researchers also reported similar result [4]. Figure 13 depicts the potential heating capacity as a function of pump pressure for 0.60 × 80° nozzle. The potential heating capacity was determined by multiplying the measured flow rates and net heating values for each fuel. The result assumes optimal combustion conditions and 100% heat transfer. The potential heating capacity increased for all fuels with an increase in nozzle flow rates. The results indicated that SHO 50 had a higher heating potential compared to the other fuels due to higher flow rates. Similar trends were also observed for the other nozzles: 0.75 × 0.80° and 0.85 × 0.80° nozzles as pressure increased from 689.48 kPa to 1103.16 kPa.

4. Conclusion

The study included property test, seal compatibility, long-term storage, and laboratory combustion tests on SHO blends. The test results demonstrated that SHO 20 was compatible for application with residential furnaces without modification. More specifically, the findings of this study are summarized as follows:

- The physical properties of No. 2 fuel oil and SHO 20 were found to be similarly compatible with residential furnaces. The viscosity and cold weather points for SHO 20, containing 20% degummed soybean heating oil, were very similar to No. 2 fuel oil. SHO 50 has a viscosity nearly twice the ASTM recommended value for No. 2 fuel oil and much higher cold weather temperature points compared to No. 2 fuel oil. The 50% blend also had difficulty igniting with most nozzles and pressures tested. These facts, along with results from combustion tests, led to recommending the use of SHO 20 in unmodified residential oil heat equipment.
- The issue of compatibility with rubber seals and gaskets found in a typical fuel system was not a concern for SHO 20. There was no significant difference between the tensile and compression properties of Nitrile when exposed to SHO 20 and No. 2 fuel oil. With Nitrile being the current material used in fuel pumps, SHO 20 should be compatible with current systems. Viton proved to be more resistant to soybean oil. Because it is more expensive than Nitrile, it is not recommended unless a higher blend of SHO is used.
- Heat energy values showed no significant changes in value after a three month storage period. SHO and No. 2 fuel oil remained miscible for at least one year after splash blending. Chemical and biological stability of low percentage SHO blends could be achieved with methods currently used for No. 2 fuel oil.
- When the analyzer accuracy was considered, all fuels tested produced indistinguishable SO_2 emissions. No fuel tested produced over 15 ppm SO_2 for any of the optimized furnace settings. SHO 20 produced NO_x emissions similar to No. 2 fuel oil. SHO 50 produced higher NO_x emissions, which indicated an upward trend with an increased soybean oil fraction. Because SHO 20 produces lower NO_x emissions compared to SHO 50, it was the recommended blend based on emissions reduction. In terms of net heat energy per unit volume, SHO 20 also had the advantage. However, SHO 50 had the advantage when only heat production per hour in a furnace was considered.

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