Fast pyrolysis oil fuel blend for marine vessels

By

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Abstract

The main driver for the investigation of fast pyrolysis oil marine fuel blends is EU directive 2012/33/EU which aims to cut the sulphur content of marine fuel and thereby reduce air pollution caused by marine vessels.

The aim of this study was to investigate the miscibility of 3- and 4- component blends containing pyrolysis oil, 1-butanol, biodiesel (RME) and/or marine gas oil (MGO). The ideal blend would be a stable homogenous product with a minimum amount of butanol, whilst maximising the amount of pyrolysis oil. A successful blend would have properties suitable for use in marine engines. In order to successfully utilise a marine fuel blend in commercial vessels it should meet minimum specification requirements such as a flash point ≥60°C.

Blends of pyrolysis oil, RME, MGO and 1-butanol were evaluated and characterised. The mixed blends were inspected after 48 hours for homogeneity and the results plotted on a tri-plot phase diagram. Homogenous samples were tested for water content, pH, acid number, viscosity and flash point as these give indicate a blend's suitability for engine testing.

The work forms part of the ReShip Project which is funded by Norwegian industry partners and the Research Council of Norway (The ENERGIX programme).

Novelty or significance

This study represents a step forward in the understanding and development of fast pyrolysis oil marine fuel blends. No research was found in the literature on marine fuel blends containing pyrolysis oil – so this work presents completely novel results. The results may be used to identify new possibilities for pyrolysis oil fuel blends that may widen the application of pyrolysis oil (which is currently limited to boiler applications). With blended fuels it may be possible to tailor the blend to specific applications.

Keywords

Bio-oil

Blend

Biodiesel

Marine gas oil

Fast pyrolysis

1 Introduction

The main driver for the investigation of marine fuel blends is the EU Directive to cut sulphur emissions and thereby reduce air pollution[1]. The maximum sulphur content in marine fuels will be cut from 3.5% to 0.5% and 0.1% in fragile ecosystems. These limits will be phased in before January 2020 on all European seas [1]. The rule will benefit health, particular around ports where pollution from shipping often breaches EU air quality standards [1]. As both fast pyrolysis oil and biodiesel have negligible sulphur content, blending these with conventional marine fuel could potentially reduce the overall sulphur content and thereby achieve the limits set by the Directive. In addition the blended marine fuel would help reduce carbon emissions and mitigate climate change through the use of bio-based products.

Fast pyrolysis oil or bio-oil is generated through the thermal decomposition of biomass. Commercially the use of fast pyrolysis oil has been limited to small-scale power and heat generation. It is difficult to use raw pyrolysis oil as a transportation fuel due to its properties which cause issues with the long term operation of engines [2-5]. These properties include high viscosity, high acidity and low thermal stability. Blending fast pyrolysis oil with other components, in order to off-set some of its more challenging qualities, could widen its area of application. The use of pyrolysis oil blended with diesel or biodiesel has been tested successfully in a number of engines [6-10] and the work by Alcala [11] found that the polar properties of alcohols allow blends of biodiesel and bio-oil to become macroscopically stable. This study investigates whether this is also true for blends containing marine gas oil (MGO).

With blended fuel it may be possible to tailor the blend toward specific applications. The future goal is to generate a marine fuel blend, with a low sulphur content to undergo engine testing and commercialisation. As any successful blends will be targeted at marine fuel applications, the marine fuel specifications were used to provide a benchmark for desired properties. The ideal fuel blend would be a stable homogenous product with a minimum amount of alcohol, whilst maximising the amount of pyrolysis oil. In order to successfully utilise a marine fuel blend in commercial vessels it should meet minimum specification targets such as a flash point ≥60°C.

The main objective of this study was to improve understanding of 3- and 4-component marine fuel blends and their characteristics. There has been a small amount of work on the blending of bio-oil with biodiesel [11-14] but no research was found in the literature on blends containing marine fuel. The results of the blending activity were used to draw 3- and 4- component phase diagrams to establish the boundary between single phase and phase separated blends. The properties of the homogenous blends were tested in order to establish blends of interest for further development.

This work forms part of the ReShip Project which aims to produce cost-competitive pyrolysis oil based multicomponent fuel which meets the performance requirement of marine diesel engines. The ReShip project is led by Paper and Fibre Research Institute (www.pfi.no) in Norway. The project is funded by Norwegian industry partners and the Research Council of Norway (The ENERGIX programme)

2 Blend components

The 3- and 4- component blends were comprised of mixtures containing the following components in varying proportions:

- Pyrolysis oil
- Marine gas oil (MGO)
- RME biodiesel
- 1-butanol

2.1 Pyrolysis oil

Pyrolysis oil or bio-oil is a dark brown free flowing liquid with a smoky aroma. During the fast pyrolysis process biomass is heated rapidly in the absence of oxygen. The decomposition produces vapours which are rapidly quenched to prevent secondary reactions. The condensed liquids are collected and this forms the pyrolysis oil product. Fast pyrolysis of biomass is a commercially viable technology; within Europe there are sites in operation in Finland (Fortum) [15] and the Netherlands (Empyro) [16]. The pyrolysis oil produced at these plants is utilised in boilers to generate heat and power. It has been found that direct use of bio-oil in diesel engines is not possible without operational and design modifications to the engine [12] and it has not been proven at demonstration scale [16].

Fast pyrolysis oil causes problems when used in unmodified engines due to adverse liquid properties and the presence of particulates. Typical bio-oil properties are given in Table 1. Standard gaskets and seals are not compatible with the raw pyrolysis oil and lacquering of the pistons and nozzles is a common experience [16]. The presence of water in the oil causes problems for ignition and effects combustion properties [16]. Other issues with the use of bio-oil in engines include: instability, pH, particulates/contaminants.

The bio-oil used in this study was manufactured from Norwegian spruce feedstock at Aston University. The fast pyrolysis equipment consists of a fluidised bed reactor followed by char recovery and vapour condensation.

2.2 Marine gas oil (MGO)

The specification for marine distillate fuels is detailed in Table 2. The quality of the fuels decreases from left to right. For this study the focus is on DMA fuel which is given the commercial denomination of marine gas oil or MGO. Marine gas oil is made from the distillate fraction of crude oil so is easier to handle than marine fuels derived from residual fuel oil. It is the fuel most commonly used for inland marine transport [19]. The properties listed were used as the benchmark for the blended marine fuels. In general, marine fuel properties are inferior to those of diesel for road transport. It has been demonstrated by Lin et al [18] that biodiesel and marine fuel can be mixed in any proportion as these fuels are fully miscible. The MGO used in this study was supplied by Statoil in Norway.

2.3 Biodiesel (RME)

Bio-diesel is a sulphur free, clear pale yellow liquid. The biodiesel used for this study was produced through the transesterification of pure rape seed oil in order to yield rape methyl esters (RMEs) and glycerol. Typical properties of RME are given in Table 3.

Blending of biodiesel with marine fuel has been shown to improve the flash point [18]. The presence of biodiesel in fuel blends with bio-oil has also been shown to improve the lubricity, reducing long term engine wear [11]. Adding biodiesel to fuel blends reduces the kinematic viscosity so that less pumping energy is required and the oxygen in the biodiesel leads to more complete combustion [18]. The application of biodiesel in marine applications has so far been limited due to the relatively high cost compared with marine fuel [18]. The bio-diesel used in this study was purchased from Biofuels and Oils in London.

2.4 1-Butanol

In previous studies adding an alcohol to bio-oil has been shown to significantly improve the stability of bio-oil [17]. For this study 1-butanol was chosen as the co-solvent. It was found by Alcala [11] that using 1-butanol gave the widest selection of stable blends in a study of 3 and 4 component blends consisting bio-oil, alcohol (ethanol, 1-butanol or 2-propanol), biodiesel and/or conventional diesel. Alcala's work found that 1-butanol accepted the largest proportion of bio-oil in the mixture. A benefit of using 1-butanol is that it may be produced by the fermentation of biomass, so this improves the renewable credentials of blends created using this component. Typical properties of butanol are given in Table 4.

3 Experimental work

3.1 Blend preparation

The blends were prepared using the same methodology as Alcala [11]. A weighed sample of bio-oil was added to the glass container, followed by biodiesel and/or MGO. Finally the butanol was added, the container sealed and lightly shaken. All blends were prepared at room temperature (~20°C).The sample was left to settle for 48hrs before visual inspection to establish homogeneity. A photograph was taken to document the appearance and quality of the blend.

The blend recipes were selected to cover a wide spectrum of compositions in order to build representative phase diagrams. The composition of the samples created can be found in Table 5, Table 6 and Table 7. In order to represent a 4-component blend on a three sided phase diagram the ratio between MGO and RME was fixed. A ratio of 75wt% MGO and 25wt% RME was maintained in all 4-component blends. This ratio was chosen to maintain a high proportion of MGO whilst gaining some benefits from the presence of a small proportion of RME in terms of improved miscibility (see Figure 1 versus Figure 2) and the benefits that RME is said to bring to engine operation [11,18].

3.2 Characterisation

The homogeneous blends were tested for some key characteristics that gave an indication of suitability for engine testing. These were:

- Water content
- Kinematic viscosity
- Flash point
- pH and acid number

3.2.1 Water content

The water content within pyrolysis oil originates from the water contained in the original feedstock plus water generated from the pyrolysis reactions. The water content within the oil reduces the heating value of the liquid but also decreases viscosity [2]. In terms of fuel properties, water in the oil lowers the flame temperature which reduces the NO_x emissions [2]. It contributes to an increase in ignition delay period, and causes erosion and corrosion problems in injectors and fuel supply [2, 19]. Therefore water content in the fuel blend is not desirable as it does not yield any energy and can cause combustion issues. Water content for marine fuels is either not specified, because it is assumed to be zero, or is set at a low level (see Table 2). Water in standard marine fuels is seen as contamination and is typically removed on-board the vessel using centrifugation [19]. The ideal fuel blend would therefore have minimal water content.

3.2.2 Kinematic viscosity

The viscosity of bio-oil is high compared to conventional fuels. The addition of alcohol to the bio-oil helps to reduce viscosity [2] and blending with additional lower viscosity components should help further reduce the impact of bio-oil's high viscosity.

Viscosity is an important fuel characteristic. A fuel with a high viscosity increases engine deposits, requires more energy to pump the fuel and increases wear to fuel pump elements and injectors [20]. The viscosity of a fuel must be within the engine manufacturers tolerance levels or there will be poor atomisation [20], poor combustion, deposit formation and energy loss [19]. Another consideration is the relationship between viscosity and temperature, as viscosity will decrease with increased temperature. This is a challenge for a ship's fuel pre-heating system which should be capable of achieving the required viscosity under varying external conditions.

3.2.3 Flash point

The flash point is a measure of the ease of ignition of the liquid. It is defined as the lowest temperature at which the material will ignite from an open flame [21]. In diesel engines a low flash point impacts the heat release inside the cylinders as well as ignition/combustion characteristics. The minimum flash point for all fuels used in bulk on-board marine vessels is set at 60°C [19] because of the fire hazard associated with the bulk storage of fuel on board vessels, so this acts as a benchmark value for successful marine fuel blends. Testing the flash point of raw bio-oil has proven to be problematic due to high variability in the results [16]. In the literature, testing of a single bio- oil for flash point gave values varying between 40 to 110°C [16].

3.2.4 pH and Acid number

Bio-oil is always acidic due to the presence of carboxylic acids, such as acetic and formic acids [22]. The pH of bio-oil is low and in the range of pH 2-3 [16, 17] which causes major issues with corrosion. The acidity of blends containing bio-oil is one of the biggest challenges for the implementation of bio-oil and fuel blends containing bio-oil, as materials of construction must be carefully considered. Blending the bio-oil with less acidic components may help to partially off-set the corrosivity of the raw bio-oil.

The pH test gives an indication of how corrosive the blend may be, but does not indicate the concentration of acidic components [16]. The acid number is used to provide this information. The current MGO specification for acid number is very low at 0.5mgKOH/g so this parameter needs careful consideration for potential marine fuel blends.

4 Results and discussion

A large number of blends were prepared and the results plotted on phase diagrams to establish the phase boundary. It was possible to create homogeneous single phase blends using 3- or 4- components. The single phase blends were tested for a number of properties, the results of which are detailed in the sections below. The individual blend components were also tested for a number of properties shown in Table 8.

4.1 Blend homogeneity

The samples were checked visually against a strong back-light in order to establish homogeneity. The resulting phase diagrams are shown in Figure 1, Figure 2 and Figure 3. The area of phase separation is indicated on the phase diagrams. In Figure 1 and Figure 2 there are samples that appear anomalous – they show as phase separated when according to the general trend they should be single phase and hence cause an unlikely loop in the phase separation curve. These samples were blended a number of times to check the repeatability of the result, and the reader can be reassured that the results indicated on the diagrams are correct.

For the 3-component blends containing MGO the single phase and phase separated samples were easily identified (see Figure 6 and Figure 7) but it was more challenging for the blends containing RME (see Figure 4 and Figure 5). Even with a strong backlight it was sometimes difficult to establish homogeneity. The same issue was observed for the 4-component samples (see Figure 8 and Figure 9). These samples were inspected very carefully to ensure that the correct result was recorded.

When comparing the phase diagrams of the 3-component RME blends (Figure 1) with 3-component MGO blends (Figure 2) the blend proportions resulting in homogenous, single phase blends can be clearly observed. The results indicated that RME is more miscible with bio-oil and butanol than MGO. The number of single phase blends containing MGO was much smaller. It was possible to successfully blend up to 70wt% bio-oil with RME but only 40wt% bio-oil with MGO. This can be partly explained by the polarity differences between these liquids. MGO is a hydrocarbon fuel and considered a non-polar liquid, whereas bio-oil, RME and butanol contain oxygen which causes varying levels of polarity.

For the 4-component blends it was anticipated that the addition of RME would improve the miscibility of MGO with bio-oil. If the 3-component MGO blend diagram (Figure 2) is compared with the 4-component blend diagram (Figure 3) the RME does appear to improve the miscibility of MGO and bio-oil marginally. In the 4-component blends it is possible to blend up to 45wt% bio-oil. A smaller amount of butanol (30wt%) is required to obtain a single phase 4-component blend when compared to the 3-component MGO requirement of >40wt%.

A selection of the single phase blends were tested for a number of characteristic properties.

4.2 Flash point

The flash point of the single phase blends were tested and the results plotted - see Figure 10. For comparison and to understand the impact of the individual blend components on the blended sample result, the flash point of the individual components was measured and the results can be found in Table 8. An attempt was made to measure the flash point of the raw bio-oil, but as found by previous researchers [16] it was not possible to obtain a consistent and repeatable result. The 3-component blends containing RME resulted in the highest flash point results. This result was anticipated as the RME has the highest flash point of the blend components (see Table 8). The results indicate a general upward trend that the flash point increases with increasing bio-oil concentration. The most important result is that none of the single phase blends met the 60°C minimum flash point requirement defined in Table 2 for marine distillate fuels.

4.3 pH and acid number

A number of the single phase blends were tested for pH and acid number to give an indication of the acidity and corrosivity. This is an important property when considering the use of blends in ship engines. Bio-oil is highly acidic which could potentially cause issues with corrosion if used in an unmodified engine. The acid number of the individual components used in the blend recipes was measured and can be found in Table 8. In comparison to RME and MGO the bio-oil is highly acidic. The acid number results for the single phase blends are shown in Figure 11. As anticipated there is an upward trend with the acid number increasing with increasing bio-oil content. A relationship between pH and bio-oil content was not established, with a wide scatter of results between pH2-5 obtained. None of the blends met the MGO specification for a maximum acid number of 0.5mgKOH/g.

4.4 Water content

The water content of the homogenous blends was measured and results are shown in Figure 12. All blend components apart from bio-oil contain negligible water content, the water content of blended samples increased with increasing bio-oil content. A high water content fuel is not desirable.

4.5 Viscosity

The viscosity of a number of the single phase blends was measured and has been plotted in Figure 13. There is a general upward trend that as the proportion of bio-oil in the blend increases the viscosity also increases, which is to be expected. When compared to the viscosity of raw bio-oil, the addition of lower viscosity components has substantially improved this property, even with up to 60wt% bio-oil in the blend. A number of the single phase blends achieved the MGO specification limits of 1.5-6.0mm^2/s. The blends that achieved the viscosity specifications contained <40wt% bio-oil.

5 Conclusions

It was possible to prepare single phase 3- and 4- component blends containing bio-oil, 1-butanol, RME and/or MGO. The main conclusions are:

- The polarity and complex composition of the pyrolysis oil makes it difficult to create successful blends with RME or MGO without the addition of significant solvent
- MGO is less miscible with bio-oil than RME. This may be due to the relative polarity of these liquids. MGO is a hydrocarbon based fuel which contains no polar elements. Whereas RME, bio-oil and butanol all contain oxygen which cause polarity.
- The presence of RME improves the miscibility of MGO with bio-oil in 4-component blends.

- None of the single phase blends achieved the minimum flash point requirement of 60°C.
- A number of the 3- and 4-component blends containing <40wt% bio-oil met the MGO viscosity specification.
- The flash point of the alcohol used in the blends has the greatest influence on the overall flash point of the blend
- The other components in bio-oil blends help to mitigate some of the negative properties associated with bio-oil, such as viscosity.

Based on the results of this work no blends containing bio-oil, butanol, RME and/or MGO appear acceptable for marine use when comparing them to current marine fuel specifications. For future work there needs to be some careful thought about the strategy for the creation of marine fuel blends. It may not be possible to match all current DMA/MGO fuel specification levels with fuel blends containing bio-oil due to the acidity, water content and flash point. Marine engine suppliers will need to be consulted to ensure that unmodified engines can cope with these acidic fuels, or more resistant materials may need to be used for components vulnerable to corrosion. An alternative strategy may be the creation of new specifications for marine fuels containing bio-liquids.

Due to the issue of low flash point when using butanol as a solvent, future investigations of marine fuel blends containing bio-oil should include the use of alternative solvents. For example, the use of higher alcohols such as 1-hexanol or ethylene glycol.

6 References

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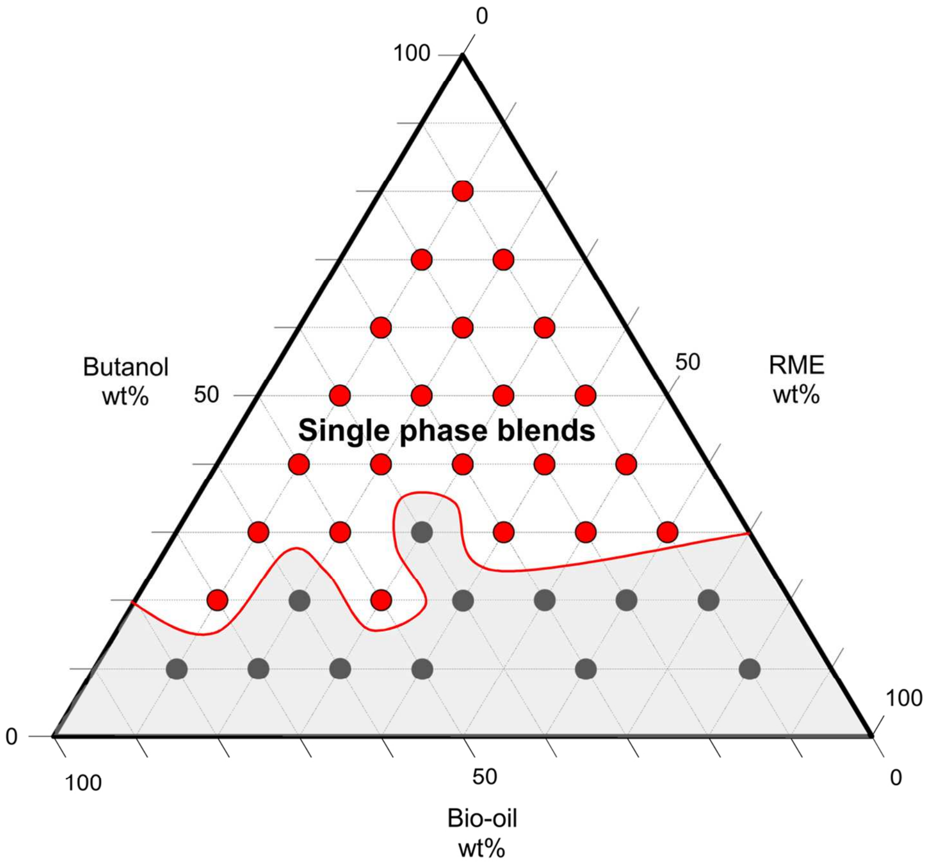

Figure 1. Phase diagram for 3-component bio-oil, butanol, RME blends
122x109mm (300 x 300 DPI)

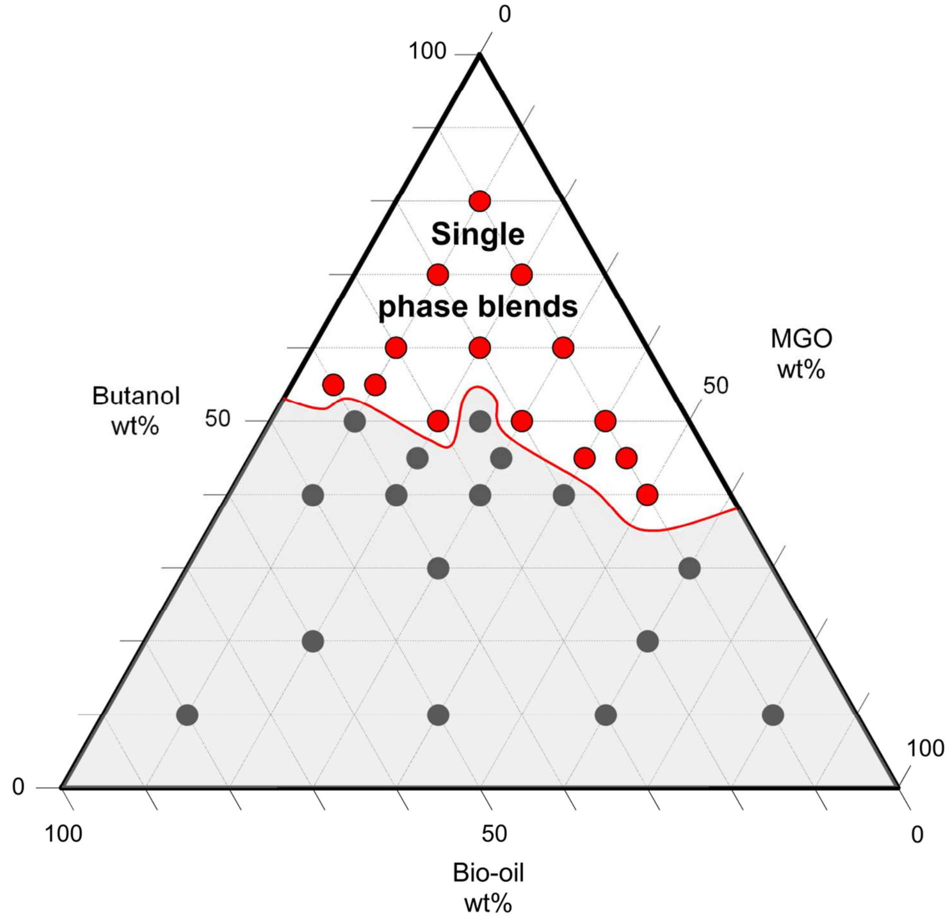

Figure 2. Phase diagram for 3-component bio-oil, butanol, MGO blends
125x117mm (300 x 300 DPI)

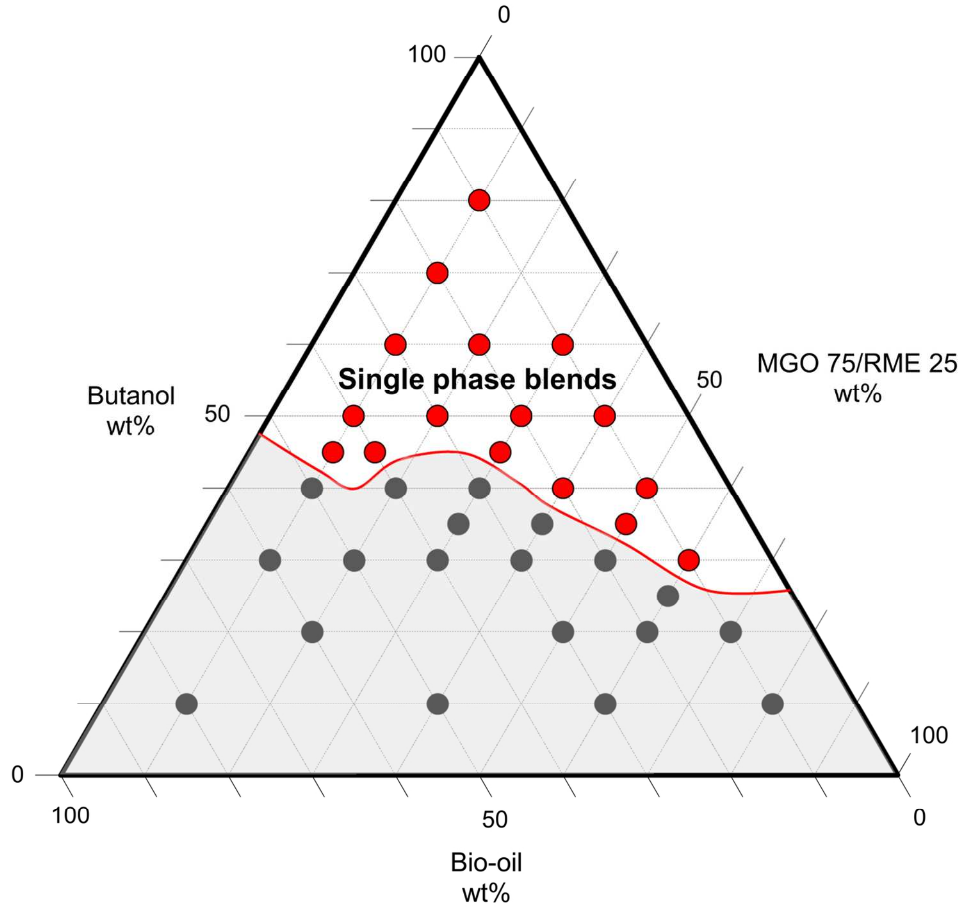

Figure 3. Phase diagram for bio-oil, butanol, RME, MGO blends
126x119mm (300 x 300 DPI)

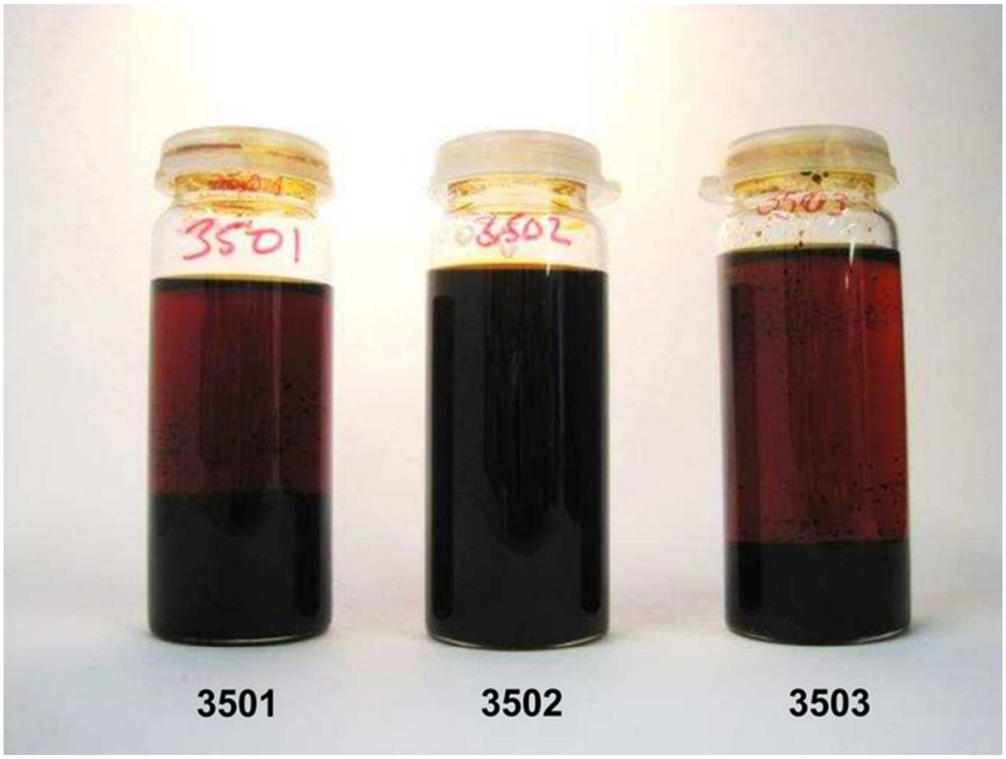

Figure 4. Samples 3501, 3502, 3503. 3-component RME blends
56x42mm (300 x 300 DPI)

Figure 5. Samples 3516, 3517, 3518. 3-component RME blends
57x43mm (300 x 300 DPI)

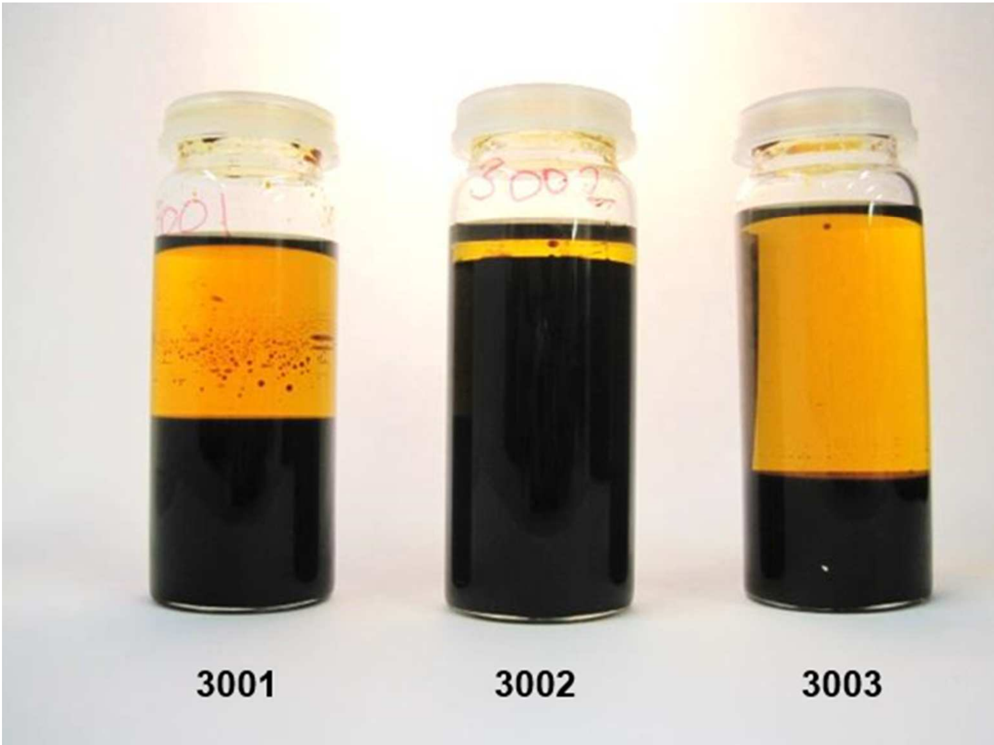

Figure 6. Samples 3001, 3002, 3003
203x152mm (72 x 72 DPI)

Figure 7. Samples 3012, 3013, 3014. 3-component MGO blends
56x42mm (300 x 300 DPI)

Figure 8. Samples 4004, 4005, 4006. 4-component blends
57x43mm (300 x 300 DPI)

Figure 9. Samples 4013, 4014, 4015. 4-component blends
57x43mm (300 x 300 DPI)

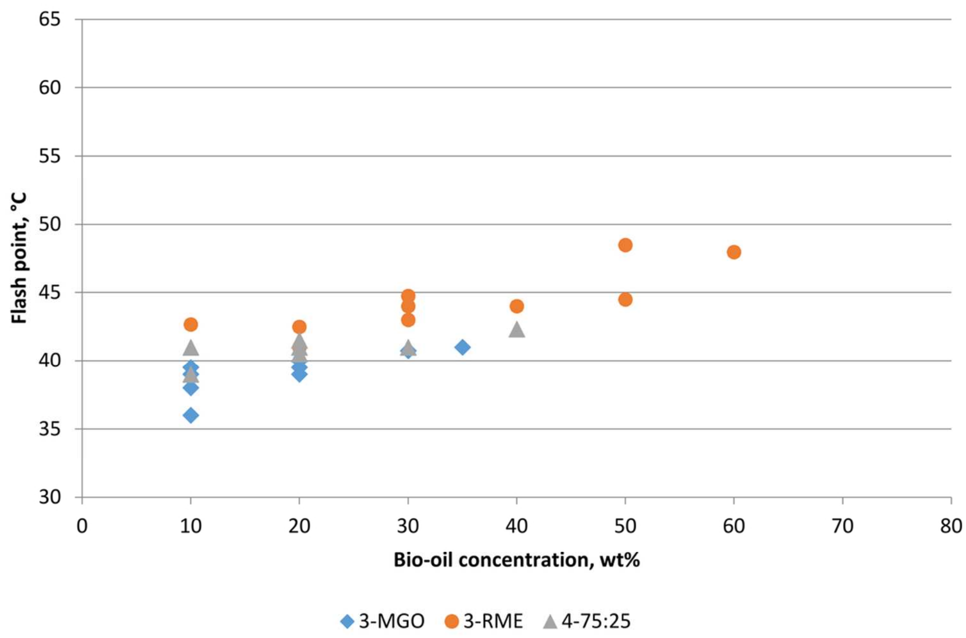

Figure 10. Single phase blends, flash point °C
102x67mm (300 x 300 DPI)

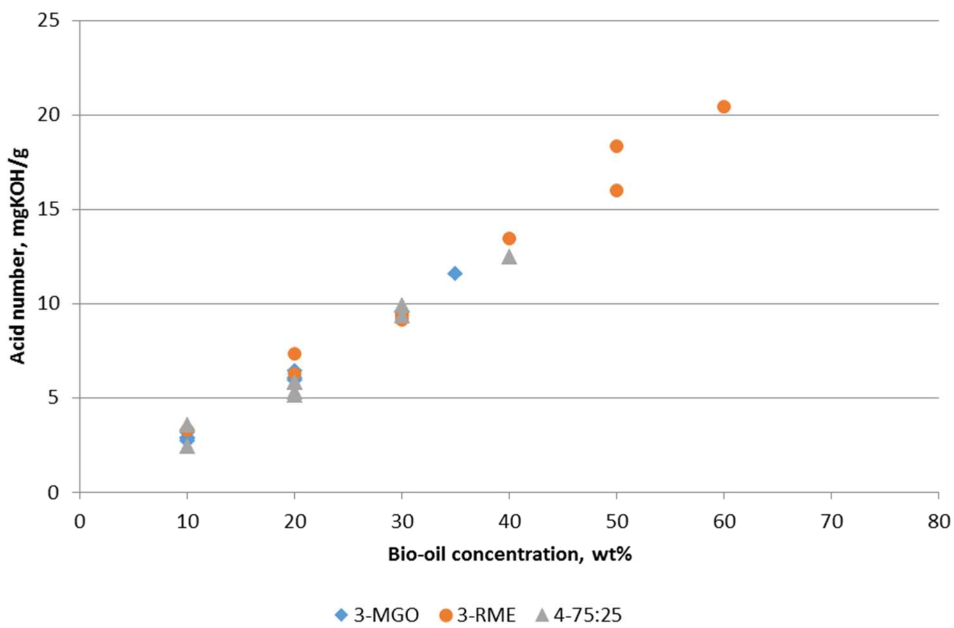

Figure 11. Single phase blends, acid number mgKOH/g
331x216mm (72 x 72 DPI)

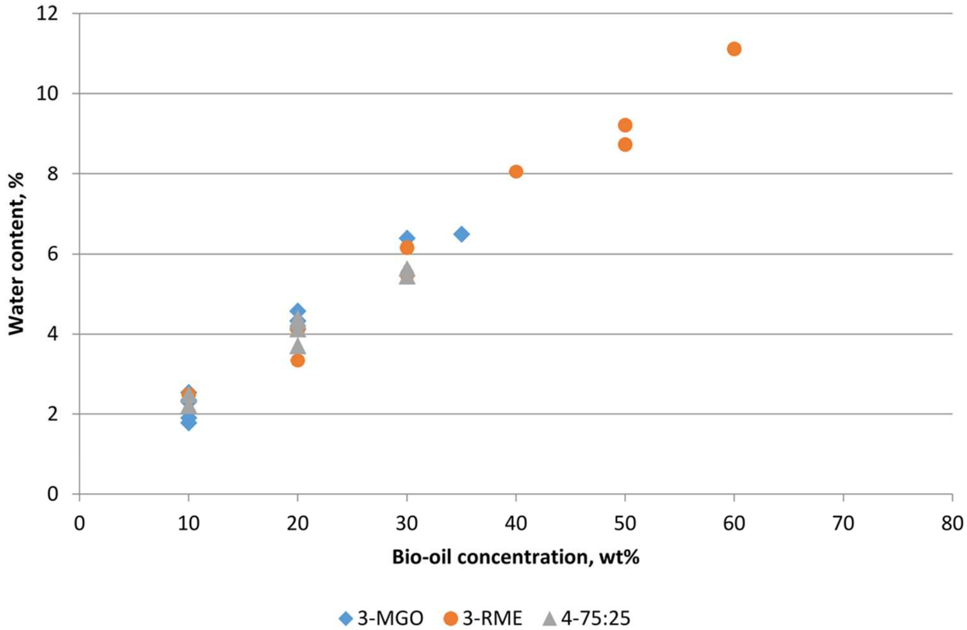

Figure 12. Single phase blends, water content %
103x68mm (300 x 300 DPI)

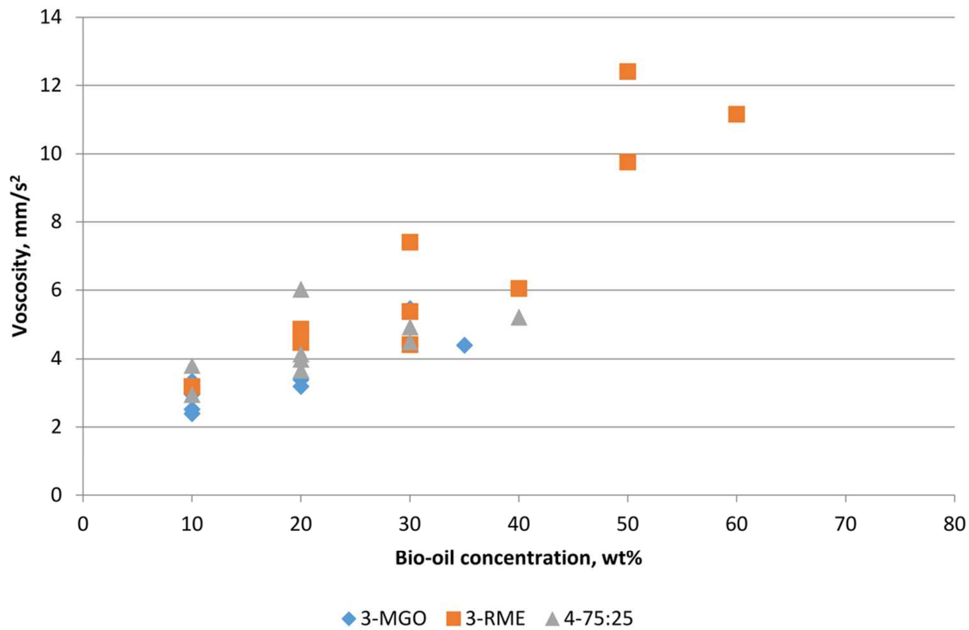

Figure 13. Single phase blends, viscosity mm/s2
103x67mm (300 x 300 DPI)

Fast pyrolysis oil fuel blend for marine vessels (Tables)

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Table 1. Typical bio-oil properties [17]

Physical property	Typical value	Bio-oil
Moisture content	wt%	25
pH		2.5
Density	kg/m^3	1200
Elemental analysis		
C	wt%	56
H	wt%	6
O	wt%	38
N	wt%	0-0.1
HHV as produced	MJ/kg	17
Viscosity	cSt (40°C)	30-85 (25% water)
Solids (char)	wt%	0.1%
Vacuum distillation residue		Up to 50%

Table 2. Requirement for marine distillate fuels [19]

Characteristic	Unit	Limit	Category ISO-F				Test method reference
			DMX	DMA (MGO)	DMB	DMC	
Density at 15°C	kg/m^3	Max.	-	890	900	920	ISO 3675 or ISO 12185
Viscosity at 40°C	mm^2/s	Min. Max.	1.40 5.50	1.50 6.00	- 11.0	- 14.0	ISO 3104 ISO 3104
Flash point	°C	Min. Max.	- 43	60 -	60 -	60 -	ISO 2719
Pour point (upper) - winter quality - summer quality	°C	 Max. Max.	 - -	 -6 0	 0 6	 0 6	 ISO 3016 ISO 3016
Sulphur	% (m/m)	Max.	1.00	1.50	2.00	2.00	ISO 8754 or ISO 14596
Cetane index	-	Min.	45	40	35	-	ISO 4264
Carbon residue	% (m/m)	Max.	-	-	0.3	2.5	ISO 10370
Ash	% (m/m)	Max.	0.01	0.01	0.01	0.05	ISO 6245
Appearance			Clear and bright		-	-	
Water	% (V/V)	Max.	-	-	0.3	0.3	ISO 3733
Acid number	mgKOH/g	Max.	0.5	0.5	0.5	0.5	ASTM D664

Table 3. RME Biodiesel properties [20]

Property	Unit	RME
Density	g/cm^3	0.8828
Viscosity	mm^2/s	4.3401
Pour point	°C	-8
Total glycerine	%	0.12
Free glycerine	%	0.010
Acid number	mg KOH/g	0.16
Ester content	%	99.2
Calculated cetane index		61.5
Flash point	°C	107

Table 4. Typical butanol properties [11]

Property		1-butanol
Molecular weight		74.1
Density	kg/m^3	806
Boiling temperature	°C	117.7
Flash point	°C	30
Refractive index		1.397

Table 5: RME 3-component blend compositions

Sample no.	Bio-oil	RME	Butanol	Single phase
	wt%			Yes/No
3501	50	40	10	No
3502	50	10	40	No
3503	30	60	10	No
3504	30	10	60	No
3505	80	10	10	No
3506	10	80	10	No
3507	10	10	80	No
3508	60	20	20	No
3509	40	30	30	No
3510	20	40	40	No
3511	30	20	50	No
3512	60	10	30	No
3513	50	20	30	No
3514	40	10	50	No
3515	30	30	40	No
3516	20	10	70	No
3517	20	20	60	Yes
3518	20	30	50	Yes
3519	30	40	30	Yes
3520	50	30	20	Yes
3521	40	40	20	No
3522	70	10	20	Yes
3523	40	20	40	Yes
3524	10	20	70	Yes
3525	10	30	60	Yes
3526	10	40	50	Yes
3527	10	50	40	Yes
3528	20	50	30	Yes
3529	30	50	20	No
3530	70	20	10	No
3531	60	30	10	No
3532	10	60	30	No
3533	20	60	20	No
3534	10	70	20	No

Table 6: MGO 3-component blend compositions

Sample no.	Bio-oil	MGO	Butanol	Single phase
	wt%			Yes/No
3001	50	40	10	No
3002	50	10	40	No
3003	30	60	10	No
3004	30	10	60	Yes
3005	80	10	10	No
3006	10	80	10	No
3007	10	10	80	Yes
3008	60	20	20	No
3009	40	30	30	No
3010	20	40	40	No
3011	25	25	50	No
3012	40	10	50	No
3013	10	40	50	Yes
3014	20	20	60	Yes
3015	10	20	70	Yes
3016	20	10	70	Yes
3017	10	30	60	Yes
3018	20	60	20	No
3019	10	50	40	Yes
3020	20	30	50	Yes
3021	30	20	50	Yes
3022	30	30	40	No
3023	40	20	40	No
3024	35	10	55	Yes
3025	35	20	45	No
3026	25	30	45	No
3027	15	40	45	Yes
3028	10	45	45	Yes
3029	40	5	55	Yes
3030	10	60	30	No
3031	20	50	40	No

Table 7: 4-component blend compositions

Sample no.	Bio-oil	MGO/RME(75:25)	Butanol	Single phase
	wt%			Yes/No
4001	50	40	10	No
4002	50	10	40	No
4003	30	60	10	No
4004	30	10	60	Yes
4005	80	10	10	No
4006	10	80	10	No
4007	10	10	80	Yes
4008	60	20	20	No
4009	40	30	30	No
4010	20	40	40	Yes
4011	20	20	60	Yes
4012	20	10	70	Yes
4013	40	10	50	Yes
4014	30	20	50	Yes
4015	30	30	40	Yes
4016	10	30	60	Yes
4017	10	60	30	Yes
4018	20	30	50	Yes
4019	20	50	30	No
4020	40	20	40	No
4021	50	20	30	No
4022	30	40	30	No
4023	10	70	20	No
4024	10	50	40	Yes
4025	10	40	50	Yes
4026	20	60	20	No
4027	40	15	45	Yes
4028	35	30	35	No
4029	25	40	35	No
4030	15	50	35	Yes
4031	15	60	25	No
4032	45	10	45	Yes
4033	60	10	30	No
4034	30	50	20	No
4035	25	30	45	Yes

Table 8. Component properties

	Flash point, °C	pH	Viscosity @ 40°C, mm/s^2	Acid number, mgKOH/g	Water content, wt%
1-butanol	30	-	-	-	-
Bio-oil	-	2.12	102.31	42.3	14.68
RME	160	-	4.22	0.21	-
MGO	67	-	5.38	0.04	-