The use of liquid biofuels in heating systems: a review

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Collaborative Task: Alternative Fuels

Abstract

European Union has set the 2020 strategy to increase the share of renewable energy use to 20% by 2020. Currently, most attention is focussed on the use of alternative fuels from biomass for energy purposes. These alternative fuels are called bioliquids. This paper reviews the current experimental works that have been performed on the combustion of vegetable oil, biodiesel and bioethanol in various heating combustion units. This review focuses on the feasibility of bioliquids use in heating systems as well as their "environmental friendly" potential.

1. Introduction

In the context of greenhouse gas (GHG) emissions reduction, the use of fuels produced from biomass is unavoidable. The European Parliament as adopted a directive that defines a 20-20-20 plan to reduce by 2020 GHG emissions from 20 percent compared with 1990 levels. The plan also promotes an increase of 20 percent in renewable energy use and finally, 20 percent of energy efficiency improvement by 2020. In this directive, European Union has defined a mandatory 10 percent goal to be achieved by all Member States for transportation fuels produced from renewable energy sources [1]. Liquid fuels from biomass are currently biodiesel and bioethanol and they are already used worldwide in the transportation sector. These can also be burnt for heating and combined heat and power (CHP) production. Biofuels are distinguished in the 2009/28/EC directive following to their use: "biofuel" means liquid or gaseous fuel for transportation produced from biomass whereas "bioliquid" means liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass [2].

Domestic heating oil varies between countries but most fuels are similar to diesel fuel, also known as Number 2 fuel in the USA. Domestic heating oil is also known as gasoil in European countries, which is similar to transportation diesel fuel although with a higher sulphur content (up to 1000ppm). However, some companies sell low sulphur fuel oils and these are practically transport diesel fuels with a maximum of 7 percent of biodiesel incorporation in diesel fuel in Belgium.

The aim of this paper is to present a review on published experimental works in the combustion of bioliquids used for heating purpose. Unfortunately the economical and life cycle analysis are not presented. The first paragraph presents a short description of the processes for biofuels production. Then, the following paragraphs review the status of the research for each biofuel.

2. Bioliquids production

Bioliquids are liquid fuels produced from biomass for energy purposes other than transport [2]. Their production is schematised on Figure 1. First generation biofuels are the ones conventionally produced from triglyceride fuels (biodiesel) and sugar or starch feedstocks (bioethanol). They can substitute conventional fuels in engines, either entirely or partially. The increase of food crops used for biofuels production has led to a decrease in the world food supply so that there is a possibility of competition between food and fuel production [3]. The increasing concern and criticism over the sustainability of first-generation biofuels has raised the interest of developing fuels produced from non-food biomass. These fuels are called second generation biofuels. They are produced from ligno-cellulosic materials (cellulose, hemicellulose and lignin) through two main conversion routes:

- Biochemical: cellulose and hemicelullose are converted to sugar prior to its fermentation to produce ethanol
- Thermo-chemical: pyrolisis/gaseification technologies to produce syngas that is synthesized into diesel fuel, aviation fuel...

Second generation biofuels are not yet produced commercially and still face major constraints to their development. As these fuels are not yet available on the market, we only present first generation biofuels production processes (triglycerides fuels and alcohol fuels).

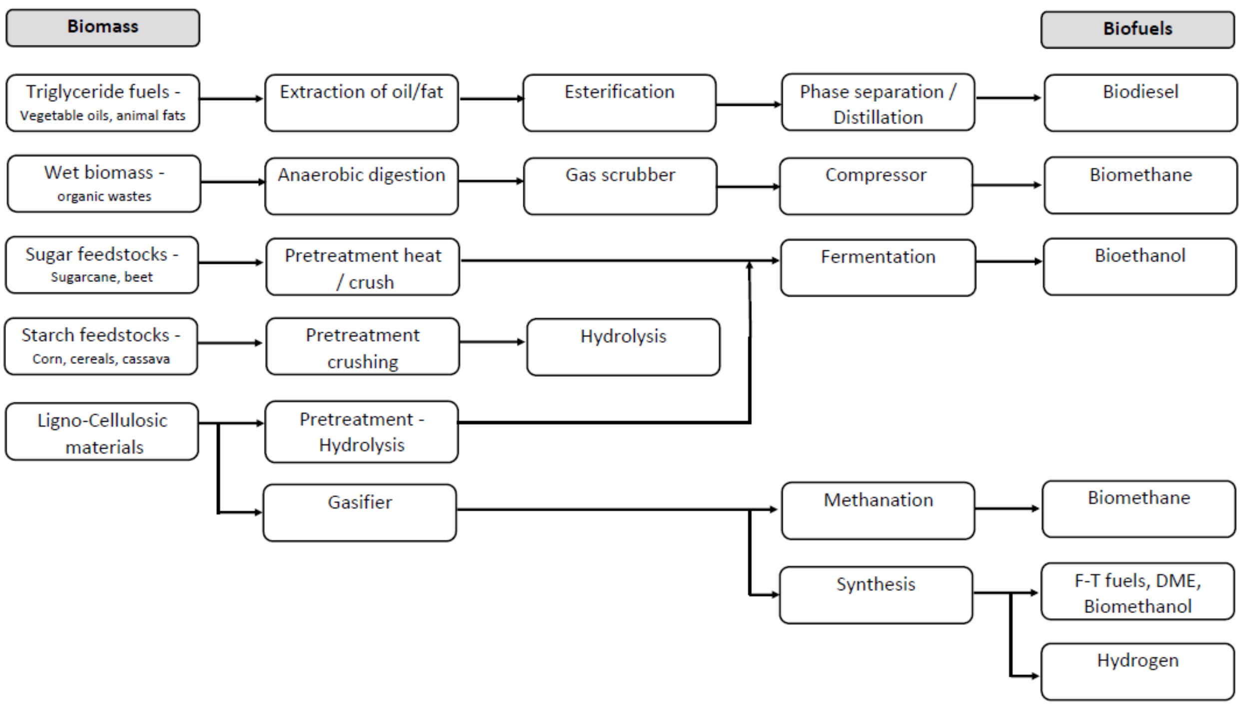

Figure 1: Different pathways for biomass conversion to biofuels [4]

2.1. Triglyceride fuels

Vegetable oils are mainly produced by mechanical extraction from seeds (rapeseed, jatropha, soybean, etc) and chemical extraction from seedcakes with solvents. Straight vegetable oils have been burnt in internal combustion engines with minor changes in the engine (heating the fuel or mixing with diesel fuel) [5]. Vegetable oils have although a high viscosity and a low cetane number. These properties could be problematic in combustion systems and a solution to improve them is to produce biodiesel by transesterification. In the transesterification process, the fatty acids of plant oils are reacted with alcohol (methanol, ethanol) in the presence of a catalyst to produce esters. When methanol is used, methylesters are produced and are commonly referred to Fatty Acid Methyl Ester (FAME) or biodiesel.

2.2. Alcohol fuels

Bioethanol is the most common biofuel produced worldwide, mainly in USA (corn ethanol, 24.4 bn l in 2007) and in Brazil (sugar cane ethanol 18.0 bn l in 2007) [4]. The fuel is produced by fermentation of sugar plants (sugar beet, sugar cane) or fermentation of starchy plants (wheat, corn). The ethanol produced from these plants is the same as the one that can be found in any alcoholic beverages. The use of bioethanol as a direct blend in petrol increases but, in Europe, most of the production is converted into Ethyl tert-butyl ether (ETBE) [6]. It is synthetised by mixing the ethanol and isobutylene and is used as an oxygenated gasoline additive for enhancing the octane number [7].

3. Bioliquids combustion in heating systems

There are three types of substituting liquid fuels that have been studied: straight vegetable oils, biodiesel and bioethanol. Most of heating systems that burn liquid fuels have been developed for fuel oil (diesel fuel or kerosene for vaporizing pot-type burner) so that most studies have been performed on biodiesel because it has similar properties to diesel fuel.

3.1. Straight Vegetable oils

Straight vegetable oils have been tested in internal combustion engines with upstream adaptations (dual fuelling, blending, preheating) or minor changes in the engine (fuel filter, injection pump) [5, 8]. Some researchers have questioned to use this oil into heating systems. The physico-chemical properties are of high importance to evaluate the compatibility of the fuel with the considered combustion system. Properties of vegetable oils from various crops are listed in Table 1 and must be compared to the ones of diesel fuel in Table 2. Vegetable oils have the advantage of having almost no sulphur content and other residues [9]. Moreover, the heating value is only 10% below the fuel oil heating value on a mass basis.

As for engines, the high viscosity of vegetable oils could be problematic but these could be used in burners that are designed for viscous fuel oil (heavy fuel oil). Vaitilingom et al. [14] have studied the combustion of rapeseed oil in a 260kW boiler equipped with a burner adjusted to use a fuel oil with a viscosity close to that of a rapeseed oil one. The burner was also fitted with a fuel preheating system since there was no possibility to start up the system with an oil temperature under 80°C. Moreover, the fuel injection pressure had to be increased. This study shows that rapeseed oil can be used in adapted commercial burners with good results in term of efficiency and pollutant emissions, as it is the case for internal combustion engines. Alonso et al. have studied combustion of vegetable oils and diesel fuel blends in a 27kW boiler [10, 19-21]. For rapeseed oil, fuel viscosity increased as rapeseed oil was added [10]. So, it was necessary to increase the fuel injection pressure to improve fuel vaporisation. For sunflower and soybean oils, CO emissions decreased when the oil was added. However, nothing could be concluded for NO_x emissions: it was unchanged, increased or decreased in some cases [19-21].

Table 1: Properties of some vegetable oils

Properties	unit	Rapeseed[1]	Soybean[2]	Sunflower[3]	Corn[2]	Jatropha[4]
HHV	MJ/kg	37.6 - 39.7	39.6	39.6	37.8 - 39.6	39.1
LHV	MJ/kg	36.8	37	36.5 – 36.9	36.3	
Viscosity 40°C	mm²/s	35.1 - 37.4	33	33.9 - 37.1	34.9 - 35.1	35.4 - 36
Density 15°C	kg/m³	911.5 - 921	913.8 - 925	915 - 920	910 - 915	917
Flash point	°C	246	254	272 - 274	276 - 277	186-240
Cetane number	-	37.6	38	36.7 - 37.1	37.5 - 38	23-51
Residual Carbon	%mass	0.31	0.24	0.28	0.22	0.07-0.8
Iodine value	g/100g	94 - 120	117 - 143	132	119.4	92-112
Sulphur content	%mass	0 - 0.03	0.01	0.002 - 0.01	0.01	0-0.13
Saponification number	mg KOH/g	172 - 197	195	191	194	103-209
Ash content	%mass	0.006	0.006	0.01	0.01	0.03
C	%mass	79.6		78.2		76.11
H	%mass	11.4		12.2		10.52
O	%mass	8.97		10		11.06
Fatty acid profile	% mass					
Myristic	C 14:0	0.06	0	0	0	0
Palmitic	C16:0	3.5 - 4.7	11.9 - 13.9	6.4	6-11.8	14.2
Palmitoléic	C16:1	0.24	0.3	0.1	0	0.7
Estéaric	C18:0	0.9 - 3	3.1 - 4.1	2.9	2	7
oléic	C18:1	54.1 - 64.1	10.8 - 23.2	17.7	24.8-44	44.7
Linoléic	C18:2	22.3 - 27.2	11.3 - 54.2	72.9	48-61.3	32.8
Linolénic	C18:3	7.14 - 8.2	6.3 - 17.6	0	0	0.2
	C>20	0 - 3	31	0	0.3	0

References: [1][10-14], [2][11-13, 15, 16], [3][9, 11-13, 15, 16], [4][11, 17, 18].

Table 2: Heating oil properties

Properties	unit	Heating oil
HHV	MJ/kg	45.1
LHV	MJ/kg	42.9
Viscosity	mm²/s	2.7 (40°C)
Density 15°C	kg/m³	855
Flash point	°C	64
Cetane number	-	52
Residual carbon	%mass	<0.3

Sulphur content	g/kg	1.59
Ash content	%mass	<0.01
C	%mass	86.9
H	%mass	13.1

Vegetable oils combustion is possible in heating system with some minor changes. As for combustion in internal combustion engines, it is necessary to reduce fuel viscosity either with a preheater or by mixing the plant oil with diesel fuel. The resulting viscosity being still above the one of diesel fuel, it is necessary to increase the fuel injection pressure to get a better fuel vaporisation and fuel-air mixing. Generally speaking, CO emissions seem to decrease when the combustion of vegetable oils (or diesel-vegetable oil blends) is compared to the combustion of reference fuel.

Finally, an inappropriate storage over a long period causes oil oxidation, hence higher viscosity and filtration problems [8]. So, in heating systems, there must be a high concern over vegetable oils storage conditions as, unlike the case of vehicles, the tanks are often filled once a year.

3.2. Biodiesel

The main problems linked to vegetable oils in combustion systems are caused by the high viscosity of the oils (around 35 mm^2/s at 40°C compared to 2.7mm^2/s for gasoil). The aim of fatty acid transesterification with methanol is mainly to reduce the oil viscosity. The products of transesterification are generally fatty acid methylesters with a composition depending on the initial oil fatty acids composition. Biodiesels have similar physical properties to diesel fuels and are good candidates to petroleum diesel fuel substitution. Biodiesel technical properties are listed in Table 3 while quality requirements are defined in the standards EN14213 for biodiesel use as heating oil [22].

Table 4 lists biodiesel properties of biodiesels produced from various crops. The higher heating value is around 12% lower than the one of diesel fuel. Biodiesel viscosity is still higher than diesel fuel viscosity (4mm^2/s compared to 2.7mm^2/s) but is of the same order than diesel fuel viscosity.

Burning biodiesel into heating systems seems to have a considerable environmental potential in terms of pollutants emissions reduction. The researchers have shown that biodiesel addition into diesel fuel seems to decrease most of pollutant emissions such as CO, SO_2, VOC and particles. However there is no clear trend for NO_x emissions.

Batey [31] has tested into conventional home heating units blends of 20 percent soy-based biodiesel into 80 percent of low sulphur diesel fuel. Compared to pure diesel emissions, fumes opacity was very low as well as CO emissions. NO_x emissions were lowered of 20% with the mixture of diesel/biodiesel. Krishna et al [27, 32-34] have also worked on biodiesel combustion in domestic space heating equipment. Globally the results show a reduction in CO emissions and NO_x emissions. Macor et Pavanello [35] have burnt biodiesel into a 400kW boiler and have compared its emissions to conventional heating oil emissions. Combustion product analysis was quite complete: CO, SO_2, NO_x, aldehydes, VOC, PAH and particles. They found that NO_x emissions were unchanged while CO emissions were lower for biodiesel. Particles, VOC and PAH were also lower for biodiesel while formaldehydes emissions increased of 100%. That is explained by the fact that biodiesel contains oxygen and promotes carbonyl group formation.

Lee et al. [36] have studied the combustion in a household boiler of a mixture of 20% soybean-based biodiesel into heating oil. NO_x emissions were unchanged but there was 20% less particles. Mixtures of soybean-based biodiesel (20% and 50%) into diesel fuel have also been tested by Jiru et al. [37] into a space heating boiler. For a given nozzle and a given fuel injection pressure, there was no significant difference between the reference fuel and the 20% biodiesel blend in terms of CO and NO_x emissions. However, the 50% blend showed higher NO_x emissions. Finally, some researches have focussed on vaporizing pot-type burners [29, 38]. Barnes et al. report their results on kerosene-biodiesel blends combustion in a vaporizing burner used for heating or cooking [38]. In almost all cases, the burner was fouled and blocked within a short period of time. They supposed that the build-up of fouling was due to polymerisation of the biodiesel set off by heat.

Table 3: Technical properties of biodiesel [23]

Common name	Biodiesel
Common chemical name	Fatty acid (m)ethyl ester
Chemical formula range	C14-C24 methylesters or C15-25H28-48O2
Kinematic viscosity (40°C)	3.5 – 5.2 mm²/s
Density (15°C)	860-894 kg/m³
Flash point	150-180°C
Solubility in water	insoluble
Reactivity	Stable but avoid strong oxidizing agents

Table 4: Biodiesel properties depending on the vegetable oil used for its production

Properties	**unité**	**Rapeseed[1]**	**Soybean[2]**	**Sunflower[3]**	**Corn[4]**	**Jatropha[5]**	**FT fuel[6]**
HHV	MJ/kg	40.5- 41.6	39.8 - 41.3	39.8 - 41.3	41.1	39.8 - 40.8	47.05
LHV	MJ/kg	37.2	37	38.95			43.98
Viscosity 40°C	mm²/s	4.2 - 6.7	4 - 5.2	4.6	3.6 - 4.2	4.4 - 5.3	2.2
Density 15°C	kg/m³	857- 882	880 - 865	860 - 884	873 - 884	867	800
Flash point	°C	180 - 192	168 - 185	157 - 183	139 - 154	147.5	99.5
Cetane number	-	51 - 59.7	45 - 60.9	46.6 - 60.9	60.9	59.2	52
acidity	mg KOH/g		0.16	0.14	0.16		
Ester content	%		98.2	97.1	97.3		
C	%mass		77.09				85.49
H	%mass		12.35				14.51
O	%mass		10.52				0
N	%mass		0.01				
S	%mass		0.01				

References: [1] [13, 24, 25], [2][13, 18, 24-27], [3][18, 24-26], [4][24, 25], [5][28, 29], [6][30]

3.3. Alcohol fuels

Bioethanol is often associated with internal combustion gasoline engines because its properties are similar to gasoline. Gasoline is rarely used in heating systems for safety reasons: its flash point is around 0°C while diesel fuel flash point is around 60°C. Moreover diesel fuel is cheaper. However several researchers have studied the possibility of burning alcohol fuels in burners and this section presents their results. Bioethanol properties are listed in Table 5. The lower heating value of ethanol is 35% lower than that of the diesel. It is also important to note that ethanol flash point is around 13°C, which is still low and causes problems for safe storage in heating applications. Moreover, bioethanol is less viscous than diesel and that can lead to lubrification problems in the pumps (Table 6).

Barroso et al. [40] have tested bioethanol into a 100kW experimental boiler. They have had to adapt flame security device for ethanol flames as the flame signature was different. In fact the base of the flame was blue and the flame detector was replaced by a detector developed for gas-fired boilers. They report another problem linked to the low vaporizing pressure of bioethanol. Bubbles have been noticed in the pump and cavitation problems have been avoided with a tank placed higher than the pump. The pump performance was also affected by the low viscosity of bioethanol. Finally the energy content is lower as the heating value and the density are lower (Table 6). The quantity of injected fuel has to be adapted for bioethanol. Barroso et al [40] proposed two ways: to increase the fuel injection pressure or to change the injection nozzle. The last solution was more easily applicable as the fuel injection pressure should be 2.24 times higher to get the same energy content.

Table 5 : Properties of various alcohols compared to diesel and gasoline [39]

	Methane	Methanol	Dimethyl ether	Ethanol	Gasoline	Diesel
Formula	CH_4	CH_3OH	CH_3OCH_3	CH_3CH_2OH	C_7H_{16}	$C_{14}H_{30}$
Molecular weight (g/mol)	16.04	32.04	46.07	46.07	100.2	198.4
Density (g/cm^3)	0.00072[a]	0.792	0.661[b]	0.785	0.737	0.856
Normal boiling point (°C) [30]	−162	64	−24.9	78	38–204	125–400
LHV (kJ/cm^3) [31]	0.0346[a]	15.82	18.92	21.09	32.05	35.66
LHV (kJ/g)	47.79	19.99	28.62	26.87	43.47	41.66
Exergy (MJ/l) [30]	0.037	17.8	20.63	23.1	32.84	33.32
Exergy (MJ/kg) [30]	51.76	22.36	30.75	29.4	47.46	46.94
Carbon Content (wt%) [30]	74	37.5	52.2	52.2	85.5	87
Sulfur content (ppm) [32]	~7–25	0	0	0	~200	~250

[a]Values per cm^3 of vapor at standard temperature and pressure.
[b]Density at $P = 1$ atm and $T = -25$ °C.

In another study, Asfar and Hamed [41] have tested alcohol-diesel mixtures in an experimental combustion unit cooled with water. They tested blends of 5, 10 and 20% by volume of alcohol into diesel fuel mixed with isobutanol in order to have a miscible solution. Flame emissivity and soot formation decreased with the alcohol addition into diesel. They report an optimum of 10% of alcohol. Beyond this value, there was no significant change. Finally, NO_x emissions were reduced as flame temperature decreases with alcohol addition.

Finally, Prieto et al. [42] have tested methanol and ethanol blended into diesel fuel in a 120 kW experimental combustion unit. NO_x emissions were not significantly reduced with alcohol addition but unburned hydrocarbons and soot emission were reduced.

Table 6: Properties of diesel compared to bioethanol [40]

Parameter	Unit	Gasoil	Bioethanol
Chemical name	–	From $C_{10}H_{20}$ to $C_{15}H_{28}$	C_2H_5OH
Carbon (C)	%m	85.08	52.14
Hydrogen (H)	%m	13.31	13.13
Oxygen (O)	%m	1.38	34.73
Nitrogen (N)	%m	<0.1	0.00
Sulphur (S)	%m	0.13	0.00
Ash (A)	%m	0.00	0.00
Humidity (W)	%m	0.00	0.00
Stoichiometric air	Nm^3/kg	~10.67	~6.95
High Heating Value	MJ/kg	45.54	29.80
Low Heating Value	MJ/kg	42.51	27.43
Density at 20 °C	kg/m^3	863	788
Flash temperature	C	64	13
Ignition temperature	C	230	366
Boiling temperature at atmospheric pressure	C	160–385	78.5
Vaporization pressure at 20 °C	bar	0.003	0.059
Vaporization pressure at 45 °C	bar	–	0.25
Kinematic viscosity at 40 °C	mm^2/s	4.3–5.2	1.04
Kinematic viscosity at 20 °C	mm^2/s	–	1.54

4. Conclusion

The substitution of traditional fossil fuels has driven researchers to evaluate the possibility of burning fuels produced from biomass (bioliquids) in heating systems. The published works on bioliquids are mainly on biodiesels as their properties are closer to conventional heating oil properties. Biodiesel could be burned in conventional burners without any modification. Straight vegetable oils or alcohol fuels have also been studied. Straight vegetable oils require some modifications as the preheating of the oils or changing the fuel nozzle/injection pressure. As for bioethanol, their use is more problematic because of storage safety, low viscosity and low energy density compared to diesel fuel.

Generally speaking, bioliquids have a considerable environmental potential in terms of pollutants emissions reduction. Pure bioliquids combustion or blends of bioliquids/diesel decreases most pollutants emissions: CO, SO_2, particles emissions are reduced. However, no conclusion can be drawn for NO_x emissions. In some cases, they are reduced, unchanged or increased. The perspectives of our work are to evaluate the effect of fuel composition on flame temperature in an experimental boiler burning biodiesel fuels from various origins.

Nomenclature

bn l	billion litre
CHP	Combined Heat and Power
ETBE	Ethyl tert-butyl ether
FAME	Fatty Acid Methyl Ester
HHV	Higher Heating Value

LHV Lower Heating Value
PAH Poly aromatic Hydrocarbon
VOC Volatile organic compound

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