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Jatropha curcas crude oil as heat transfer fluid or thermal energy storage material for concentrating solar power plants

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ABSTRACT

Valorisation of local and low cost eco-materials has become an imperative for the sustainable development of Concentrating Solar Power (CSP) in West Africa. In this study, *Jatropha curcas* crude oil is studied as alternative heat transfer fluid or thermal energy storage material, particularly as a thermal oil substitute. The thermal stability of *Jatropha curcas* crude oil was experimentally investigated. The crude oil was aged by through thermal treatments, using galvanised steel and 316L stainless steel reactor under steady-state and dynamic conditions up to 210 °C. The change in physico-chemical parameters of *Jatropha curcas* crude oil, such as viscosity, flash point, acidity number, water content, iodine value, peroxide value and chemical composition was monitored. The results indicate a relative stability of the total acid number during the dynamic and pseudo-static tests both in galvanised steel and in 316L stainless steel reactors. The results also show that the measured viscosity at 40 °C remains practically constant after tests in steady-state conditions. This is also the case of the total acidity number. The evolution of iron and zinc contents of the oil shows that the use of 316L stainless steel material highly limits the degradation process of *Jatropha curcas* crude oil. Therefore, the main benefits of *Jatropha curcas* crude oil are its sustainable character, wide availability, good energy storage density, low cost and absence of use conflict. The oil can, therefore, be considered a suitable candidate for thermal applications up to 210 °C, such as small scale CSP plants.

Introduction

Concentrating Solar Power (CSP) technology is nowadays considered as alternative solution for the future sustainable electricity generation. This is especially the case in the Sahelian region where abundant direct solar resource is available while the electricity access rate is very low (35%) (International Energy Agency (IEA), 2016). Nowadays, CSP technology of small scale (10 to 500 kWe) with temperature below 250 °C is expected as adapted solution for West African countries (Py et al., 2013). In this context, the CSP4Africa project has been implemented with the aim of developing a small scale CSP pilot, operating with a maximum temperature of 210 °C, that should help in the study of the cost effectiveness of such kind of plants (N'Tsoukpoe et al., 2016). To achieve this purpose, locally made components and low cost materials should be preferably used in order to increase the sustainability of the technology (N'Tsoukpoe et al., 2016) and reduce investment costs. Despite the great experience built-up in CSP plants, the technology is still facing several limitations. One of these limitations is the improvement or the substitution of the heat transfer fluid (HTF) or thermal energy storage material (TESM).[1] Although extensive use of thermal oils has been demonstrated in commercial applications, these fluids exhibit a number of disadvantages such as low decomposition temperature, low density, high inflammability, high vapour pressure (up to 10 bars), harmfulness and high cost (Alva et al., 2017; Gil et al., 2010). In the perspective of sustainable development, it is necessary to establish a set of safe, adapted and non-toxic thermal oils for use in CSP plants. The use of a locally available vegetable oil without conflict of interest as HTF or TESM could then be a possible suitable solution.

Jatropha curcas crude oil (JaCCO) is a non-edible vegetable oil commonly found in most of tropical and subtropical regions where the

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[1] Beyond transferring heat, the HTF can also be used as thermal energy storage material (TESM) to store energy in an insulated tank to guarantee a continuous power generation when sun energy is not available. For the sake of simplicity, the expression « heat transfer fluid » (HTF) is generally used in this paper and it should generally be understood as heat transfer fluid or thermal energy storage material (TESM).

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Table 1
Comparison of JaCCO characteristics with those of thermal oils that are used in CSP plants (Therminol VP-1, Xceltherm 600 and Syltherm XLT).

Parameters	Therminol VP-1 (Eastman Chemical Company, 2016)	Xceltherm 600 (Radco Industries, 2017)	Syltherm XLT (The Dow Chemical Company, 2017)	JaCCO
Composition	Diphenyl oxide/biphenyl	Paraffinic mineral oil	Dimethyl polysiloxane	Triglycerides/ free fatty acids
Max bulk temperature (°C)	400	316	260	–
Flash point (°C)	124	193	47	220–240[b,c]
Fire point (°C)	127	216	54	275[c]
Atmospheric boiling point (°C)	257	301	200	295[c]
Pour point at 1013 mbar (°C)	12	−29	−11	3[c]
Total acidity (mg·KOH g^{-1})	<0.2	–	0.01	11[c]
Kinematic viscosity at 40 °C ($mm^2 \cdot s^{-1}$)	2.48	15.5	1.1	30–35[c,d,e]
Dynamic viscosity at 40 °C (mPa·s)	2.61	15	1	36
Dynamic viscosity at 210 °C (mPa·s)	0.37	0.55	0.23	1.73[b]
Density at 40° C ($kg \cdot m^{-3}$)	1068	841	834	926
Density at 210° C ($kg \cdot m^{-3}$)	904	736	660	802[b]
Thermal conductivity at 210 °C ($W \cdot m^{-1} \cdot K^{-1}$)	0.11	0.13	0.06	0.11[f]
Specific heat capacity at 210 °C ($kJ \cdot kg^{-1} \cdot °C^{-1}$)	2.075	2.643	2.171	2.509[g]
Thermal storage capacity at 210 °C ($kJ \cdot m^{-3} \cdot °C^{-1}$)	1876	1945	1433	2012[g]
Cost (€·t^{-1})	25000[a]	–	29400[a,h]	835
Energy storage cost for ΔT = 100 °C (€·kWh^{-1})	464[a]	–	573[a]	12
Greenhouse gas emissions ($kg \cdot CO_2eq \cdot kg^{-1}$)	3	–	–	2[g]

[a] These costs do not include handling, in particular, transport cost, which may be significant.
[b] Results from our own measurements.
[c] Silitonga et al. (2011)
[d] Sundarapandian and Devaradjane (2007)
[e] Blin et al. (2013)
[f] Hoffmann et al. (2016)
[g] Hoffmann (2015)
[h] Dumont et al. (2015)

solar resource is widely available. The plant is widely available in West Africa and is subject of increasing interest for straight vegetable oil production (Blin et al., 2013; Ndong et al., 2009). JaCCO is already commonly used as an alternative fuel in compression-ignition engines (Jain and Sharma, 2010; Pramanik, 2003).

JaCCO presents usually a chemical composition corresponding in most cases to a mixture of 95% triglycerides and 5% free fatty acids, sterols, waxes and various impurities (Blin et al., 2013). The composition of the oil and some of related properties may depend on the variety of the *Jatropha curcas* used for the oil production and on the extraction method (Belewu et al., 2010; Karaj and Müller, 2011). The JaCCO generally contains around 18 to 24% of saturated fatty acids and 73 to 79% of unsaturated fatty acids (Lu et al., 2009; de Oliveira et al., 2009).

Currently, the demand for edible oils such as soybean, corn, and palm oil has grown rapidly and their prices have increased tremendously in recent years (Chhetri et al., 2008). So, it is important to justify the use of these oils for other purposes. Hence, the contribution of non-edible oils such as JaCCO could become significant as a non-edible plant oil source for vegetable oil production (Chhetri et al., 2008). However, there are very few studies available in the open literature about the potential use of this particular vegetable oil for CSP applications (Hoffmann, 2015; Hoffmann et al., 2016). Thus, preliminary comparisons between JaCCO and well-established commercial oils currently used in industrial CSP (Orosz and Dickes, 2017; Vignarooban et al., 2015) have been performed (Table 1).

Although JaCCO properties such as chemical, flash point, fire point, pour point, total acidity, kinematic viscosity and dynamic viscosity are known to be different to that of well-known thermal oils (Therminol VP-1, Xceltherm 600 and Syltherm XLT[2]), the max bulk temperature, atmospheric boiling point, density, thermal conductivity, specific heat capacity and thermal storage capacity are nearly similar. More interesting, JaCCO cost (850 € t^{-1}) is at least 30 times less expensive than the synthetic Therminol VP-1 (25,000 € t^{-1}) and Syltherm XLT (29,400 € t^{-1}). According to Fernandez et al. (2010), the materials with a cost of about 5000 € t^{-1} can be considered as a relevant thermal energy storage candidate. The cost to store 1 kWh of energy at 210 °C with JaCCO is 12 € kWh^{-1} which is 48 times less expensive than Syltherm XLT (573 € kWh^{-1}).

However, vegetable oils usually start to deteriorate when exposed to oxygen, temperature or moisture (Gertz et al., 2000). The level of degradation increases as the temperature or the length of exposure increases (ASTM D6743-01, 2001). This degradation is affected and accelerated by many factors such as high temperature (Yaakob et al., 2014), fatty acids (Knothe and Dunn, 2003), unsaturated components (Knothe and Dunn, 2003), light (Jain and Sharma, 2011), the presence of transition metals that possess two or more valance states (Schaich, 1992), and other parameters (Ashraful et al., 2014; Carareto et al., 2012; Schaich, 1992; Wan Nik et al., 2005).

Nevertheless, one of the main limitations of oils used as HTF or TESM is the difficulty of predicting its durability in a solar plant. This durability is generally linked to the thermal stability of the oil at the maximum temperature at which no significant degradation of the oil properties are observed. Thus, it appears necessary to evaluate the ability of JaCCO to be used in high temperature thermal processes regarding this major issue. Before specifying the conditions of the use of this oil, it is necessary to evaluate its ability to store or transfer heat.

The main objective of this work was to study the suitability and the thermal stability of JaCCO for its use as heat transfer fluid or thermal storage material up to 210 °C. For this purpose, the crude oil was aged in galvanised steel and 316L stainless steel reactors, using various thermal treatments called dynamic, pseudo-static and static treatments. The changes of physico-chemical parameters as well as metal content of JaCCO have been monitored during

[2] Xceltherm 600 has been used for a CSP plant operating below 200 °C (e.g. Holaniku at Keahole Point, 500 kW_e (National Renewable Energy Laboratory, 2017a)) or between 120 and 300 °C (e.g. Saguaro Power Plant, 1 MW_e (National Renewable Energy Laboratory, 2017b)) while Syltherm XLT has been considered for <200 °C (e.g. Sun2Power, 2.5 kW_e (Dumont et al., 2015)).