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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 ($mg\cdot KOH\ g^{-1}$)	<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 ($€\cdot t^{-1}$)	25000[a]	–	29400[a,h]	835
Energy storage cost for $\Delta T = 100$ °C ($€\cdot kWh^{-1}$)	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)).

thermal treatments. The temperature of 210 °C was chosen for the following reasons:

- 210 °C is the maximum operating temperature set for the CSP4Africa plant, a pilot of small CSP power plant of 100 kW_{th} under construction on the campus of 2iE (N'Tsoukpoe et al., 2016), which is the main trigger of this study. At first glance, the temperature of 210 °C may appear relatively low. However, according to a literature survey that was conducted on small scale CSP plants with an electric power output of <500 kW (N'Tsoukpoe et al., 2016), only 2 of the 12 CSP plants reported operate with a temperature higher than 250 °C while 9 operate below 200 °C. Indeed, most of them operate with an Organic Rankine Cycle (ORC), which requires relatively low heat input temperature level. These machines are designed for medium temperature (150–250 °C), so there is no need for higher temperatures.
- the use of the oil is not only for CSP applications but for any industrial process requiring the use of a heat transfer fluid at medium temperature. The study should be understood from a broader perspective, not focused on CSP, although it was the starting point. For instance, JaCCO may be used for drying or preheating in industrial processes. It can also be used for sorption refrigeration where the temperature levels needed ranges from 100 to 200 °C.

Experimental investigation of the thermal stability of JaCCO

Material

The JaCCO supplied by the Belwet Company[3] in Burkina Faso was used in the present study. The initial characteristics of the oil were determined at the beginning of each test because the physical and chemical properties of the oil are impacted by the quality of the feedstock, the processing production and storage conditions.

Methods

Thermogravimetric analysis and differential thermal analysis

In order to estimate the temperature range in which the HTF degradation takes place, a procedure based on the thermogravimetric technique was used. Thermal degradation characteristics were carried out with a thermogravimetric analyser (SETSYS Evolution TGA 16/18, Setaram Instrumentation). The fast-scan test was carried out by heating the sample from room temperature to 500 °C with a rate of 10 $°C \cdot min^{-1}$, under nitrogen atmosphere. For the long-scan test, the sample was heated at 210 °C and maintained at this temperature level during 25 h, under nitrogen atmosphere.

Tests in reactor

To study the thermal stability of JaCCO, the key parameters of the oil subjected to different thermal conditions were experimentally monitored. With the aim to stay as much as possible close to the operating conditions of a CSP plant, three types of tests were carried out: dynamic, pseudo-static and static tests.

The reactor is composed of a 14 cm diameter container, 15 cm in height and 2 mm thickness, covered by a square lid 24 cm in side. The tests were carried out by loading about 2.5 l of JaCCO in the reactor. The reactor was always closed and the remaining air in the reactor was not extracted. Two different reactors have been used: one made of 316L stainless steel (commonly used in CSP plants) and the other one made of galvanised steel. The goal was to know whether the behaviour of the oil in contact with these materials is the same and therefore if galvanised steel, which is less expensive and highly available, could be used for the projected application.

For the dynamic tests, the oil in the reactor was heated with a thermal bath up to 210 °C. Once this temperature was reached, the reactor was removed from the thermal bath and cooled down to room temperature. The lid was removed and a sample of 150 ml was collected and used for various analyses. The remaining oil in the reactor was again submitted to the same procedure, which was repeated 10 times.[4]

For the pseudo-static tests, the oil was heat up to 210 °C, maintained at this temperature for 8 h using a thermal bath before it was naturally cooled down. This procedure has been repeated 10 times.

The static test was carried out with the stainless steel reactor. The reactor was closed and introduced in a furnace chamber at 210 ± 2 °C for 500 h[5] under air atmospheric conditions. All experiments were performed in triplicates in order to ensure the reproducibility. The oil temperature was monitored using a thermocouple with an uncertainty of ±1 °C. The difference of temperature measured between the inner wall and the centre of the oil was <1.5 °C when the temperature of 210 °C was reached. Therefore, it assumes that the temperature in the reactor was practically uniform and the measurements reasonably depict the behaviour of the oil.

Physical and chemical properties of JaCCO

The dynamic viscosity of samples was measured at 40 °C by using OmniTek S-Flow 3000 viscometers according to the ASTM D7279 method. The dynamic viscosity at 210 °C was carried out with a Rheometer Ares-G2 of TA Instrument at atmospheric pressure under nitrogen flow.

Flash point was measured with an open-cup Setaflash 3′Plus′ model 33000–0 analyser from STANHOPE-SETA according to the ASTM D93A standard method.

The total acid number was determined by potentiometric titration according to the ASTM D974 method.

Iodine value was determined by the ISO 3961 method (Wijs analytical method).

The peroxide value of sample was determined by the potentiometric titration method according to the NFT 60–220 method.

The Karl Fischer titrimetric method ISO 8534 was used to measure water content in oil.

Metal content of sample was analysed by the Spectro LNF-Q100 spectrometer according to the ASTM D6595 method.

All measurements were performed in triplicates and the average values were taken. Maximum deviation was <5%.

Results and discussion

Fast and long term scan thermal analysis

Fig. 1a presents the fast-scan TG and DTA behaviour of JaCCO under nitrogen atmosphere while heated up to 500 °C.

The curves show a thermal stability of JaCCO up to a temperature of 265 °C. Above this temperature, a loss of the weight is observed. The observed weight loss may due to either the vaporisation of the oil[6] or

[3] Belwet Company produces JaCCO in Burkina Faso. Jatropha seeds collected from Burkina Faso are cold pressed and stored. From 1000 g of *Jatropha curcas* seed, approximately 278 g of oil (27.8%) is recovered. The used oil has undergone neither purification nor neutralization so that some values of initial characteristics such as acidity and water content may be high.

[4] Therefore, there is more air available in the reactor from a cycle to the following cycle, during the dynamic tests. A more rigorous procedure of the effect of cycling would require a fresh 2.5 L batch of oil for each number of cycles. Hence, the dynamic tests, pseudo-dynamic tests and the static tests should not be compared directly to each other; each test should be considered for itself and provides useful information.

[5] 500 h is the preferred test duration recommended by the American Nation Standard D6743–01″ "Standard Test Method for Thermal Stability of Organic Heat Transfer Fluids" (ASTM D6743–01, 2001), which indicates that longer tests duration could be adopted. This duration tends to be the standard adopted by various authors who have investigated the thermal stability of heat transfer fluids used in CSP, for instance in Ref. (Grirate et al., 2016; Ortega et al., 2014).

[6] The boiling temperature of JaCCO under atmospheric pressure is 295 °C (Table 1). Vaporisation here refers to a physical phenomenon, which is reversible, while volatilisation of decomposition products refers to an irreversible phenomenon.

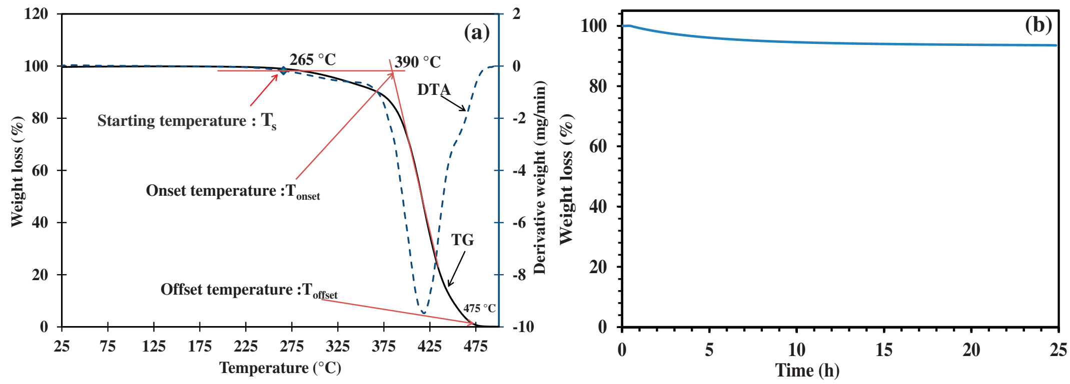

Fig. 1. Thermal behaviours of JaCCO: a) Fast scan TG/DTA up to 500 °C; b) Long term TG during 25 h at 210 °C.

the volatilisation of decomposition products, or to both. Based on previous works on other vegetable oils, it is considered here that the weight loss is mainly due to the volatilisation of decomposition products (Souza et al., 2004; Santos et al., 2004). Thermal decomposition of vegetable oils occurred in three stages, generally related to the decomposition of polyunsaturated, monounsaturated and saturated fatty acids, respectively (Lubis et al., 2015; Souza et al., 2004). The first stage observed in the temperature range of 265 °C to 350 °C could be assigned to the thermal decomposition of triglycerides, mainly composed of the polyunsaturated fatty acids. JaCCO is mainly composed of linoleic acid (C18:2). Oleic acid and linoleic acid are the dominant fatty acids while palmitic acid and stearic acid are the major saturated fatty acids found in the oil (Akbar et al., 2009).

The presence of high content of polyunsaturated fatty acids, which are generally unstable at high temperature, could have an influence on the oxidative reaction of JaCCO when used as TESM or HTF. The second stage of thermal decomposition occurred in the temperature range of 350 °C to 440 °C and could be attributed to the volatilization of triglycerides. The third stage of thermal decomposition recorded between 440 °C and 475 °C may be attributed to the volatilisation of higher molecular weight triglycerides. The curve flattering at 475 °C shows that the decomposition of JaCCO was achieved without remaining residue at this temperature or no further occurring conversion. As aforementioned, fast-scans do not provide all reliable information about a material long-term thermal stability. Thus, long term tests were also performed at 210 °C, which is below the range in which weight losses were observed during the fast-scan.

Fig. 1b illustrates the TG curve of long-term stability of JaCCO carried out at 210 °C during 25 h. After the first 10 h, about 5% of mass variation of oil was observed. The observed variation is generally attributed to the loss of water and low molecular weight compounds (Souza et al., 2004; Santos et al., 2004). Since the water content indicated by the Karl Fischer tests (0.05%) is very low compared to 5%, this mass loss could be attributed to low molecular weight compounds. This slight effect is significantly reduced after 20 h down to an additional 1 wt%. Following this, the weight remains constant during the lasts 5 h, which indicates a potential stability of JaCCO at this temperature. Thus, following dynamics, pseudo-statics and statics tests have been performed at 210 °C with larger amount of oil.

Dynamic thermal stability tests of JaCCO

Physical and chemical properties evolution

Fig. 2a shows the evolution of the kinematic viscosity of JaCCO at 40 °C under cycling in galvanised steel and stainless steel reactors. It can be seen that, the kinematic viscosity of the oil after 4, 7 and 10 cycles in both containers increased with the heating cycle number.

The increase of the viscosity in vegetable oils is usually caused by the formation of oxidized compounds and high molecular weight polymers. Kinematic viscosities obtained with tested JaCCO in the galvanised steel reactor are higher than those obtained in the 316L stainless steel reactor. These results confirm that the heating temperature and the metals coating from 316L stainless steel and galvanised steel reactors have an effect on the degradation rate process as reported by (Knothe and Dunn, 2003). The reported viscosity of the oil (at 40 °C, Fig. 2) after the 10 cycles in the stainless steel container is similar to that of ordinary (not cycled) palm oil or olive oil at the same temperature (Fasina and Colley, 2008; Tangsathitkulchai et al., 2004). So, this viscosity is not too high although it is higher than that of a commercial heat transfer fluid like Therminol VP-1 at the same temperature (Table 1). Given that viscosity decreases with temperature, the value of the viscosity will be lower than the depicted values in the operating conditions. Now, we have no knowledge of the existence of indicated limit values for viscosity; the limit values are generally given by prohibitive pressure drop or heat transfer limitations so that the decision is left to the user.

In Fig. 2b, a decrease of flash point is observed both in 316L stainless steel and galvanised reactors under cycling. In fact, this drop could be due to the decrease of double bonds (iodine value) in the fatty acid. After 10 cycles, the flash points were still above that of uncycled Therminol VP-1 and Syltherm XLT. However, the flash point decrease is likely to continue with the cycling, especially in these test conditions where the reactor is repeatedly opened for sampling purpose (air or oxygen is renewed in the reactor and oxidation may therefore be accelerated). As compared to cycling oil in galvanised steel reactor in which the flash point drops to 185 °C after 10 cycles, 316L stainless steel reactor have shown a higher final flash point of 195 °C, which remained satisfactory for CSP application.

A relative stability of the total acid number at about 15 $mg \cdot KOH \cdot g^{-1}$ is observed during the tests (Fig. 2c) for both galvanised steel reactor and 316L stainless steel reactor. Vegetable oils molecules have a tendency to be hydrolysed forming acid in the presence of water, air or oxygen. However, a water concentration <0.7% (7000 ppm), as previously mentioned by Dana et al. (Dana et al., 2003), considerably lessen thermal oxidation and hydrolytic cleavage, and no significant change in the JaCCO total acid number was observed. During cycling, a decrease of water content (Fig. 2d) from about 510 ppm to 220 ppm was monitored while an increase of peroxide values (Fig. 2e) in both reactors was observed. An increase of peroxide value in oil indicates the formation of oxidation product that promotes degradation of the oil. Peroxide values of JaCCO cycled in 316L stainless steel and galvanize steel reactors increase from 22 to 38 $mEqO_2 \cdot kg^{-1}$and 11 to 43 $mEqO_2 \cdot kg^{-1}$, respectively. According to Dana et al. (Dana et al., 2003), the high rates of water evaporation

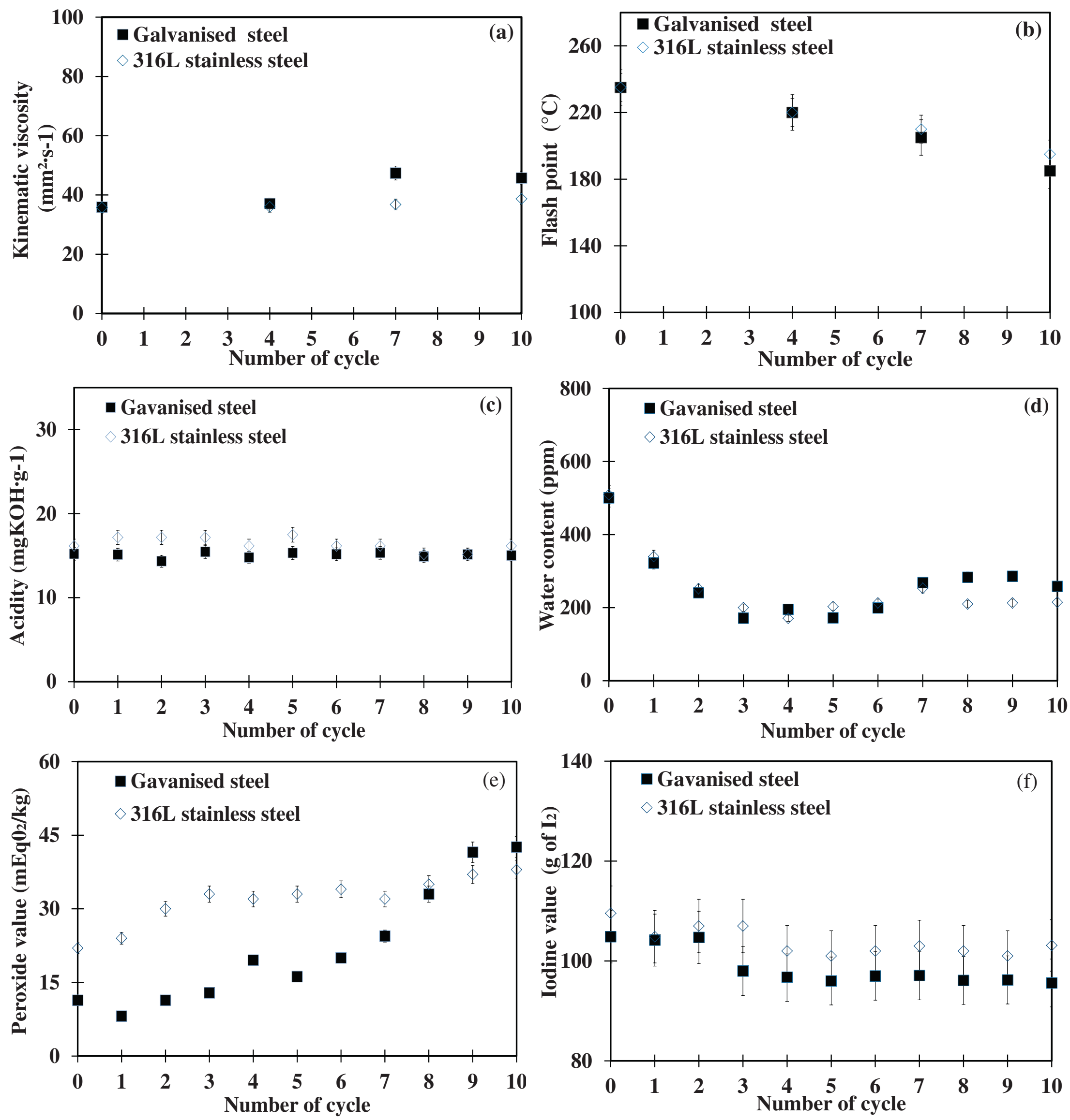

Fig. 2. Physical and chemical properties evolution of JaCCO during dynamic tests in galvanised steel and 316L stainless steel reactors: (a) Kinematic viscosity at 40 °C, (b) Flash point, (c) Total acidy number, (d) Water content., (e) Peroxide value, (f) Iodine value.

form an inert "steam blanket" which could provide a physical barrier between air (oxygen) and the oil. The low water contents (<0.1%) recorded in both reactors after tests is correlated to the related large amount of peroxide compounds.

Iodine value indicates the degree of fatty acids unsaturation in oils. A decrease of iodine value indicates that the double bonds of unsaturated fatty acids were damaged by oxidation and polymerization. Fig. 2f presents iodine values during cycling in both reactors. The major components of JaCCO concerning fatty acid chains are linoleic acid or C18:2, oleic acid or C18:1, linolenic acid or C18:3 and stearic acid or C16:0. As appreciated, the amount of iodine values of fatty acids in 316L stainless steel reactor remains constant at around 100 g I_2 g^{-1}. However, the amount of iodine values in the galvanised steel reactor tends to decrease during the heating time especially after the third cycle. This behaviour indicates that the unsaturated fatty acid chains (C18:1, C18:2 and C18:3) present in triglycerides could be responsible for the above mentioned polymerization reaction of triglycerides, causing an increase in liquid viscosity.

Metal content evolution

Fig. 3 illustrates the metal content evolutions of JaCCO during dynamic cycling in 316L stainless steel and galvanised steel reactor.

As can be seen in Fig. 3, iron content of JaCCO in galvanised steel reactor increases significantly from 3.33 to 63.59 ppm (Fig. 3a) while zinc content increases from 0 to 6.4 ppm (Fig. 3b). An increase of iron content suggests that the zinc coating layer in galvanised steel reactor starts to fail and degrades during tests by corrosion, due to high acidity level of the oil. However, iron and zinc content (<3.5 ppm) of JaCCO in 316L stainless steel reactor remains low and stable, despite slight increases. This indicates that the 316L stainless steel material is relatively suitable for the expected application. For the iron content, the final value in 316L stainless steel reactor is low (3.7 ppm) compared to that obtained for the tests in galvanised reactor (63.59 ppm). As previously observed in Section 0, this could be explained by the high peroxide value of JaCCO in the galvanised steel reactor than that in the 316L stainless steel reactor. The same trend was observed in previous study on biodegradable oil stability versus metals concentration (Knothe and Dunn, 2003).

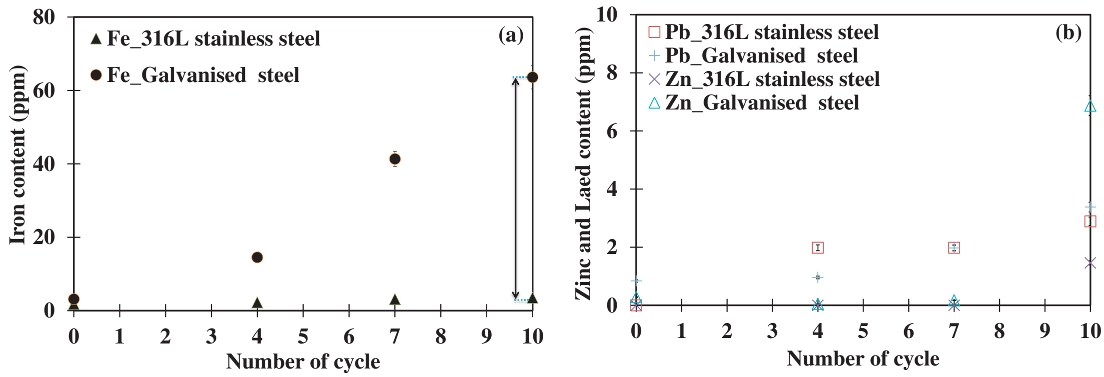

Fig. 3. Metal content evolution of JaCCO during dynamic tests in galvanised steel and 316L stainless steel reactors: (a) Iron; (b) Lead and Zinc.

In addition, we also observed that the colour of the oil samples changed to a darker colour. This could be due to oxidation or breakdown of colour pigments as showed by (Wan Nik et al., 2005). The darkness of the colour of the oils is more pronounced in the case of aged sample tested in galvanised steel reactor compared to those tested in 316L stainless steel reactor.

Thus, based on the above results, the 316L stainless steel reactor has been selected for static and pseudo-static tests.

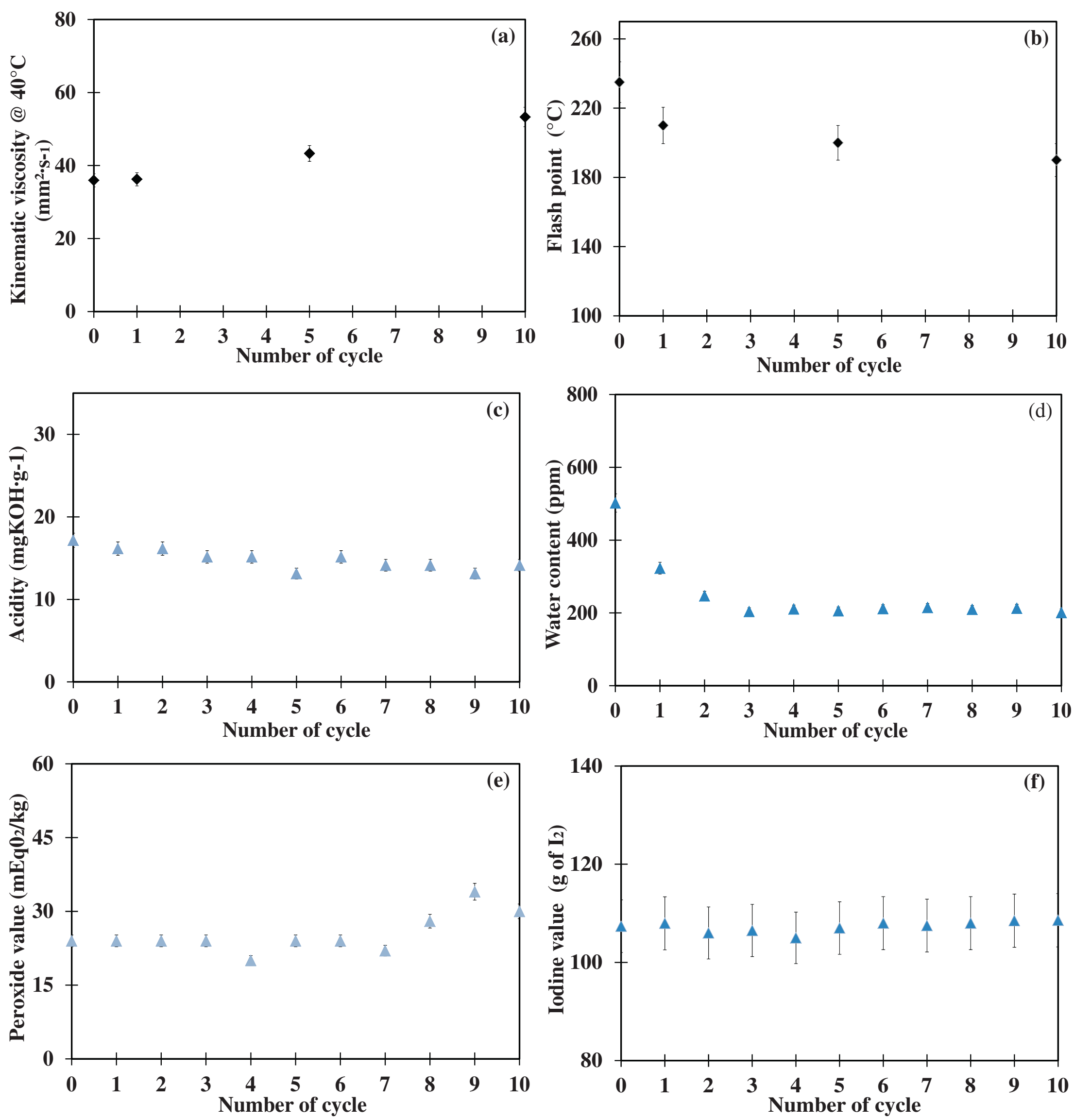

Fig. 4. Physical properties evolution during pseudo-static tests in 316L stainless steel reactor: (a) kinematic viscosity at 40 °C, (b) flash point, (c) Total acidy number, (d)Water content), (e) Peroxide value, (f) Iodine value.

Pseudo-static thermal stability tests of JaCCO

Physical and chemical properties evolution

Fig. 4 shows physical properties evolution of JaCCO during pseudo-statics tests. Fig. 4 (a) presents the kinematic viscosity evolution at 40 °C of JaCCO in stainless steel reactor during cycling.

The viscosity presents a slight increase as the number of cycle increases. These data of cycled JaCCO during pseudo-static tests suggest that the oxidative polymerization is significantly reduced compared to those observed under dynamic tests.

The evolution of flash point is illustrated in Fig. 4b. A drop of flash point is observed during pseudo-static test (8 h) along the cycles but still also above the initial flash points of Therminol VP-1 and Syltherm XLT (124 and 47 °C, respectively) after 10 cycles. Hence, the risk of hazardous fire with JaCCO is reduced as compared to other oils used in CSP plants.

Chemical properties evolutions of JaCCO during pseudo-static are presented in Fig. 4c to Fig. 4f. A relative stability in total acid number at around 15 $mg \cdot KOH \cdot g^{-1}$ (Fig. 4c) is observed. The water content presented in Fig. 4d decreases from 508 to 200 ppm, indicating its departure by vaporisation. The final value is still less than the minimum value required to induce any hydrolysis reaction of JaCCO. However, an increase of peroxide value is observed in Fig. 4e. This indicates an oxidation reaction occurring during cycles. It seems that, for each opening of the reactor, the contact of oil with air is favoured and induces significant effects. A relative stability in iodine value at around 105 $g \cdot I_2$ (Fig. 4f) is also observed. After all, the rate of degradation of JaCCO is low as compared to those from dynamic tests with galvanised steel and stainless steel reactor (Fig. 3). Indeed, no particular change in chemical properties is observed, enhancing chemical stability of JaCCO with 316L stainless steel reactor when no or limited contact with air is allowed.

Metal content evolution

Fig. 5 presents the iron content evolution of JaCCO during pseudo-statics cycling in 316L stainless steel reactor. The iron content evolution of JaCCO during pseudo-statics cycling in 316L stainless steel reactor does not indicate a significant deterioration. A slow increase of iron content from 3.09 to 4.06 ppm resulting from a low corrosion reaction is observed in 316L stainless steel reactor after tests during pseudo-statics cycling. The catalytic effect of iron is highly inhibited by using stable material as 316L stainless steel. The rate of this increase is low when compared to the dynamic tests with galvanised steel reactor (Fig. 3a). No variation of zinc and lead has been observed before and after cycling.

Although pseudo static tests carried out in this study do not allow the possibility to draw a definite finding on the thermal behaviour of JaCCO, it nevertheless makes it possible to indicate the trends and to consider rather quickly the usability of JaCCO for CSP or other medium temperature applications.

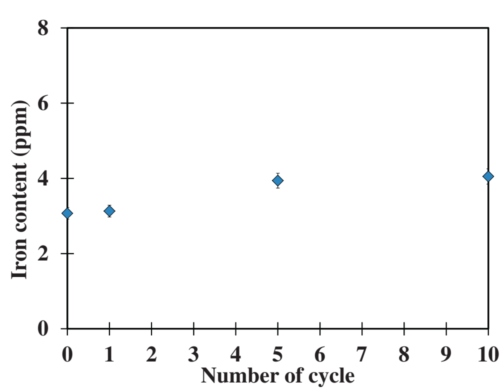

Fig. 5. Iron content evolution during static and pseudo-static tests of JaCCO in 316L stainless steel reactor.

Table 2
Physical properties, chemical properties and metal content of JaCCO before and after static tests in 316L stainless steel reactor.

Properties	Initial	After 500 h
Kinematic viscosity ($mm^2 \cdot s^{-1}$)	36	39
Flash point (°C)	235	235
Total acidity ($mg \cdot KOH \cdot g^{-1}$)	17.1	18.2
Iodine value ($I_2 \cdot g^{-1}$)	107	107
Peroxide value ($mEqO_2 \cdot kg^{-1}$)	11	16
Water content (ppm)	508	273
Iron content (ppm)	3.07	3.64

Static thermal stability tests of JaCCO

In this part, the effect of a continuous heating at 210 °C on JaCCO was studied in 316L stainless steel reactor. Table 2 presents the value of different properties of JaCCO before and after static tests.

As it can be seen, the kinematic viscosity increases slightly with heating time. Indeed, after 500 h of continuous heating, the kinematic viscosity value was beyond 39 $mm^2 \cdot s^{-1}$while it did not reach the value obtained after 115 h of discontinuous heating treatment (i.e. 10 pseudo static tests). The fact that the reactor was not opened during the whole static test could explain this result as there is no significant air renewal in the reactor.

The flash point, acid value and iodine value of JaCCO before and after heating at 210 °C were found to be nearly the same, highlighting that there is no degradation at this temperature level. However, a low increase of peroxide value was observed under heating, certainly due to the atmospheric air initially present in the reactor. Furthermore a tiny increase in iron content from 3.08 to 3.64 ppm involves low corrosion of the stainless steel reactor. Moreover, no zinc and lead were detected in JaCCO, indicating a better stability of oil due to a good compatibility of JaCCO and 316L stainless steel, which is usually used in CSP plants (Pihl et al., 2012).

From these results, it can be concluded that the presence of oxygen at high temperature is the key parameter which influences JaCCO stability. Thus, to be more thorough, further studies have to be done in an inert environment with 316L stainless steel reactor to appreciate its impact on oil degradation.

Conclusion

Prior to the present work, no fundamental investigation was made to study the potential of JaCCO used as a HTF and TESM in CSP plants or other medium to high temperature applications. Thus, thermal stability of JaCCO has been investigated in the present paper. The comparison of the energy storage density, price and flash point of the various oils, disregarding the acidity and viscosity, indicates that the proposed vegetable oil has better potential than the commonly used oils (Therminol VP-1, Xceltherm 600 and Syltherm XLT) regarding the target application. The different tests proceeded on JaCCO, particularly static tests, have shown that the oil remained relatively stable after 500 h when maintained at 210 °C. The measured viscosity, acidity and flash point remained practically constant after thermal cycling tests. The flash point during dynamic tests drops continuously from 235 °C to 185 °C after 10 cycles but still above the flash points of Therminol VP-1 and Syltherm XLT. The evolution of the chemical composition of JaCCO when handled with different container materials, especially the presence of elements such as iron and zinc, suggests that, 316L stainless steel is more suitable and compatible with JaCCO than galvanised steel.

A relevant fluid used as TESM and HTF should be an inexpensive and nontoxic liquid with the proper thermo-physical properties and long operating lifetime. The results obtained indicate that, for medium temperature application such as small scale CSP plants with operating temperatures around 210 °C, JaCCO meets most of the above requirement. However, there are some drawbacks to deal with before making a commercial deployment of JaCCO as HTF for CSP plants, particularly because of its high acidity. Nevertheless, if particular measures were taken during production and storage process of JaCCO, the initial value of acidity of the oil would be significantly reduced. Then, with a good environmental concern, JaCCO is therefore a promising innovative local HTF and TESM for CSP plants or medium temperature industrial processes.

In addition to this work, research is underway to investigate the incorporation of nanoparticles or antioxidative compounds into the JaCCO in order to improve its heat capacity, thermal conductivity and thermal stability at high temperature. Longer period tests of JaCCO under real conditions are also planned with the CSP4Africa pilot, whose construction is underway.

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Glossary

CSP: concentrating solar power
HTF: heat transfer fluid
JaCCO: *Jatropha curcas* crude oil
TESM: thermal energy storage material