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QUENCH SEVERITY OF BIOQUENCHANTS ON MEDIUM CARBON STEEL FOR INDUSTRIAL HEAT TREATMENT

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ABSTRACT: The rate of heat extraction and severity of quenching of both edible and non edible bioquenchants for industrial heat treatment was investigated using AISI 4137 medium carbon steel. Results showed that both maximum and minimum cooling rate occurred in the nucleate boiling stage and the peak cooling rates of Jatropha oil, groundnut oil, melon oil, sheabutter oil, palmkernel oil and palm oil were greater than that of mineral oil. The quench severity of Jatropha, sheabutter and groundnut oil are higher with H-factor of 5.93, 6.00 and 6.14 respectively. High heat transfer coefficient of 1583, 1180 and 1024 W/m^2K were obtained for Jatropha oil, groundnut oil and melon oil; while sheabutter oil, palmkernel oil, palm oil and mineral oil have heat transfer coefficient of 1001, 971, 828, and 589 W/m^2K respectively.
KEYWORDS: Heat transfer, Bioquenchants, Cooling rate, Quench severity, Jatropha

INTRODUCTION

Quenching of carbon steel involves heat treatment above upper critical temperature to austenitizing temperature and holding at this temperature for a specified soaking time, and then rapidly immersed in a suitable quench medium. Comparisons of different quenchants in heat treatment processes of steels are of great usefulness in order to achieve desired hardness, strength or toughness and minimizing the possibility of occurrence of quench cracks due to evolution of residual stresses Canle et al [1]. The choice of effective quenching medium after heat treatment is very critical in ensuring the achievement of desired mechanical properties; therefore, selection of a quenchant depends on the quench sensitivity of a particular grade of steel and the severity of quench medium [2]. The three stages of quenching are vapour blanket, where a vapour film surrounding the component acts as an insulating blanket reducing the heat flow from component subjected to quenching. The second stage is known as the nucleate boiling stage where the vapour film formed collapses and high heat extraction rates are achieved. The third stage known as the convective cooling stage and this begins when the temperature of the metal surface is reduced below the boiling point of the quenching liquid. Cooling rate is low during this stage [3]. The severity of quenching or the cooling power of a quench medium is estimated by measuring the thermal response of a heated probe brought in contact with it. It is a measure of the ability of a quenchant to extract heat from a sample during quenching and depends on viscosity, temperature, contamination and agitation. The cooling potential of quenching media is a critical factor in heat-treating processes because of its contribution to attaining the minimum hardenability requirement of the part or section being heat treated [4]. Cooling curve analysis method is most useful for assessing the cooling characteristics of a quenching medium [5]. Quench severity can be determined by measuring the Grossmann hardenability factor H and heat transfer coefficients. Heat transfer coefficient h is defined as the ratio of interfacial heat flux to the temperature drop across the interface. The lumped heat capacitance method (LHCM) and Grossmann method are generally used to measure heat coefficient at the quenchant/probe interface and assess the severity of quenching. In both methods, heat flux q and/or the heat transfer coefficient h are calculated directly from the measured cooling curve data. The LHCM assumes a uniform probe temperature during the cooling [6]. If the probe temperature is uniform, the heat loss Q from the probe is equal to the decrease in the internal energy of the probe. Thus

$$Q = hA(T_p - T_q) = C_p \rho V\left(\frac{dT_p}{dt}\right) \quad (1)$$

where, h is the heat transfer coefficient on the probe surface, A is the surface area of the probe, T_p is the probe temperature, T_q is the quenchant temperature, C_p is the specific heat of the probe *material, ρ is the specific density of the probe material, V is the volume of the probe material, t is the time and $\frac{dT}{dt}$ is the cooling rate of the probe.*

Using the above expression in equation (1), the heat flux is estimated as given by Goryushin et al [7]

$$q = h\left(T_p - T_q\right) = \left(\frac{C_p \rho V}{A}\right)\frac{dT_p}{dt} \quad (2)$$

The accuracy of the cooling rate calculated from measured cooling curve data determines the precision of the estimated heat flux or heat transfer coefficient. In the Grossmann technique, a hardinability factor H is defined as given in expression (3) by Fernandes [8]

$$H = \frac{\bar{h}}{2k} \quad (3)$$

The present study was carried out to assess the heat transfer rate and quench severity of various bioquenchants with conventional quench media using Grossman and Lumped heat capacitance method (LHCM) techniques for characterizing media having low and high severity of quenching.

EXPERIMENTAL DETAILS

The vegetable oils used for this work were purchased at the local Nigeria Southwestern markets and were characterized and used in the as-purchased condition. The vegetable oils that were purchased includes: jatropha oil, groundnut oil, melon oil, sheabutter oil, palmkernel oil and palm oil. Quenching performance of these oils was compared with one commercially available mineral oil designated as quintolubric 888-46 (conventional slow oil).

Chemical structure of the bioquenchants used in this work was characterized by fluid viscosity which was measured at 40^{o}C according to ASTM D445-06 standard test and the fatty acid ester composition of the vegetable oil was determined by a gas chromatographic analysis procedure using methyl ester derivatives of the different vegetable oils prepared using a Model 634 Shimadzu gas chromatograph equipped with a flame ionization detector (FID) set to 300^{o}C and a split injection system ratio of 1:30 at 280^{o}C.

The cylindrical probe of 0.37%C steel specimens of 13.5 mm dia x 70 mm fitted with a type K thermocouple to the geometric center, Fig. 1 were heated in electric furnace at the rate of 25^{o}C/min to a temperature of 850^{o}C $\pm$ 3^{o}C, and soaked at that temperature for about 1 hour. The heights of these probes were five times their diameters to ensure heat transfer in the radial direction. The thermocouple was inserted in a hole of diameter 3 mm drilled in the top surface of the probe and care was taken to ensure a tight fit and good contact condition. The heated specimens were manually and quickly transferred laterally (under 2 s) into 1000mL of the bioquenchants to be tested under static condition which was contained in a rectangular form quench bath. The probe temperature and cooling times was captured using SD card datalogger digital thermometer Model MTM-380SD in order to establish a cooling temperature versus time curve.

RESULTS AND DISCUSSION - Chemical properties

The results obtained in Table 1 shows that the vegetable oils used possess a triglyceride structure, which are completely saturated (no double bonds), monounsaturated (one double bond/fatty ester linkage), diunsaturated (two double bonds/fatty ester linkage) and triunsaturated (three double bonds/fatty ester linkage). The two most common saturated fatty esters in the vegetable oils used for this study are palmitic and stearic, while the monounsaturated ester is oleic and diunsaturated ester is linoleic. Also the chemical compositions of the steel material used for the investigation was as shown in Table 2. The steel composition satisfies the minimum carbon point required for it to be materially affected by heat treatment, since it has 37% carbon which is higher than 25%.

Table 1: Composition percentage of fatty acids present in sample of vegetable oils

Vegetable oils	Saturated acids							
	Decanoate C10:0	Lauric C12:0	Myristic C14:0	Palmitic C16:0	Stearic C18:0	Arachidic C20:0	Oleic C18:1	Linoleic C18:2
Palm oil	-	-	0.76	36.50	3.69	1.03	45.66	12.36
Palm kernel oil	3.57	50.37	17.08	8.98	8.55	-	9.23	2.21
Groundnut oil	-	-	-	13.75	9.99	1.19	39.27	32.91
Melon oil	-	-	-	17.02	20.77	-	11.00	49.26
Shea butter oil	-	-	-	4.62	74.56	1.24	18.84	0.74
Jatropha oil	-	-	-	48.34	19.81	3.68	31.85	20.26

Table 2: Chemical composition (wt %) of the Steel Used

C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu
0.37	0.23	0.06	0.05	0.79	0.12	0.10	0.02	0.003	0.26
W	As	Sn	Co	Al	Pb	Ca	Zn	Fe	
0.003	0.006	0.006	0.01	-0.007	-0.002	0.0001	0.004	97.95	

Cooling Rates

The cooling curves shows the three stages of quenching which are film boiling, nucleate boiling and convection phase Figure 1. The film phase existed for a short period of 6 seconds in all the quench media while the vapor phase existed for longer period. Cooling rates of the quenchants were significantly different from each other, and it's in two parts namely peak cooling rate and minimum cooling rate.

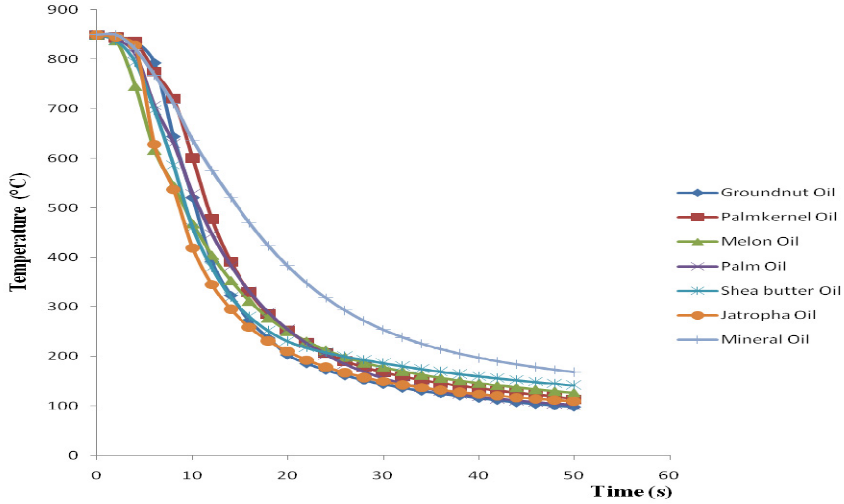

Figure 1. Cooling curve of various bioquenchant and mineral quenchant

Both maximum and minimum cooling rate occurred in the nucleate boiling stage Figure 2. In the edible bioquenchants oil i.e groundnut oil, melon oil, palmkernel oil and palm oil the maximum cooling rate were 74.6, 64.7, 61.3 and 52.3 $^{0}C/s$ with corresponding temperature of 644, 617, 550 and 707^{o}C respectively, while the non edible bioquenchants such as Jatropha and sheabutter oil had peak cooling rates of 100 and 63.2 $^{0}C/s$ at corresponding temp of 628.6 and 459.8 ^{0}C respectively.

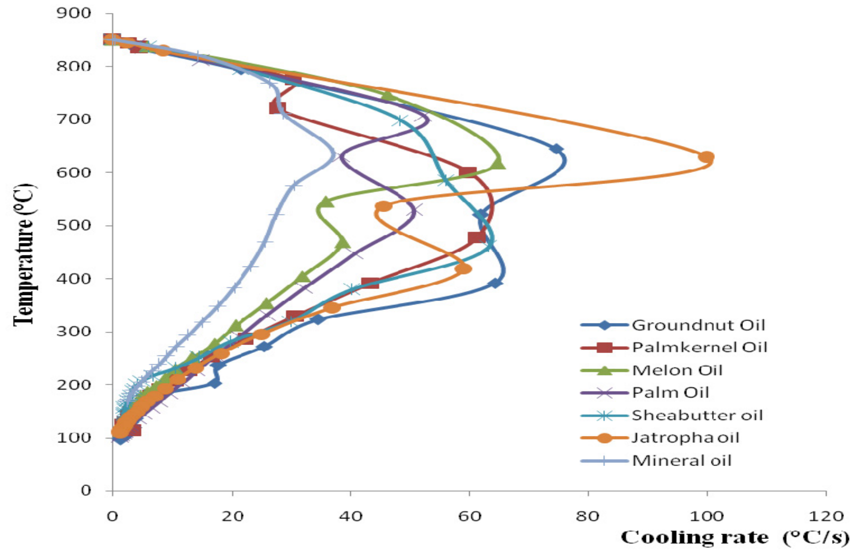

Figure 2. Cooling rate for various bioquenchants

The minimum cooling rate for Jatropha oil is 59$^{0}C/s$ at corresponding temperature of 419 ^{0}C, mineral oil and sheabutter oil shows no minimum cooling rate; however the cooling rate for the mineral oil was 37.1 $^{0}C/s$ at temperature of 637 ^{0}C. The period of occurrence of the peak cooling rate for melon oil, palm oil and Jatropha oil was 6 seconds from the start of quenching; While, sheabutter and mineral oil was 10secs. The cooling rate is higher in Jatropha oil than all other quenchants oil used. In all the quenchants the cooling rate was found to be strongly dependent on the viscosity of the quench oil and the saponification number. The higher the viscosity the lower the cooling rate and the lower the saponification number the higher the cooling rate. The cooling rate were found to be in this order

Jatropha oil>Groundnut oil>Melon oil> Sheabutter oil>Palmkernel oil>Palm oil>Mineral oil

Heat transfer coefficient and heat flux

Using the cooling curve data to determine time dependent heat transfer coefficient by lump heat capacitance methods and time average heat transfer coefficient by the Grossman method, high heat transfer coefficient of 1583, 1180 and 1024 W/m^{2}K were obtained for Jatropha, groundnut oil and melon oil while, sheabutter oil, palm kernel oil, palm oil and mineral oil have heat transfer coefficient of 1001, 971, 828 and 589 W/m^{2}K respectively Figure 3. The peak heat transfer coefficient of all the bioquenchants was higher than the conventional mineral oil which has heat transfer coefficient of 589 W/m^2. The heat transfer coefficient were found to be highly dependent on the viscosity and acid value of the quench media, and the value increases with decrease in percentage of acid value and increase in percentage of moisture content. Higher heat transfer coefficient was found with lower viscosity oils such as, jatropha oil, groundnut oil and melon oil which have viscosity of 52.6, 40.5 and 35.6 mm^2/s. The temperatures at which peak heat transfer coefficient occurs for all the quenchants was in the nucleate boiling region with sheabutter oil, groundnut oil, mineral oil, palm oil, jatropha oil, melon oil and palmkernel oil having values of 698, 644, 637, 631, 629, 617 and 601^{o}C respectively.

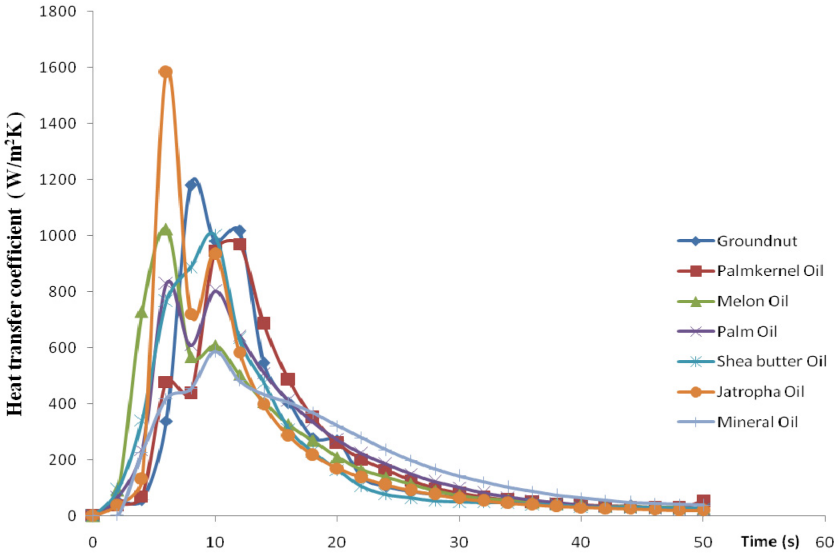

Figure 3. Variation of heat transfer coefficient of various quenching media for steels

The period of attainment for peak heat transfer coefficient for Jatropha and melon was 6 seconds, while palm oil, sheabutter oil and mineral oil was 10 seconds but groundnut oil and palmkernel oil were 8 and 12 seconds respectively. Thus palm oil, palmkernel oil, sheabutter oil and mineral oil can be used has slow quenching media, while Jatropha oil, groundnut oil and melon oil may be employed as fast quenching medium.

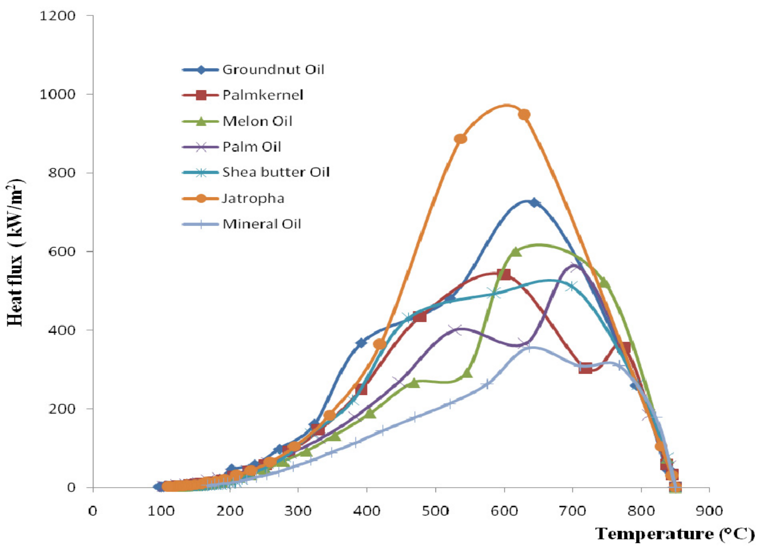

Figure 4. Variation of heat flux with temperature for various quenchants

The flux values are low in the initial quenching time due to the insulating effect of the vapour blanket for all the quench media Figure 4. However, the duration of existence for the vapour blanket stage was longer for bioquenchants media compared with the conventional mineral oil. Maximum heat flux of 948 kW/m^2 was obtained for Jatropha oil while sheabutter oil has the lowest peak heat flux of 512 kW/m^2. The heat flux obtained for all the bioquenchants media are higher than that of mineral *oil of 356 kW/m^2. The bioquenchants with higher viscosity offers greater resistance to the motion of vapour bubbles during nucleate boiling stage and thereby making supply of cold liquid to the heated surface reduced; this resulted to the lower peak heat flux transients during quenching of the steel probe in higher viscosity sheabutter oil.*

Severity of quench media

The biot number of the quenchants determined showed that for all the oils the biot number is very small and less than unity Table 3. Groundnut oil has the highest value of 0.029 as the biot number, while sheabutter oil and jatropha oil has the same value of 0.028. Palmkernel oil, melon oil, palm oil, and mineral oil were 0.024, 0.022, 0.019, and 0.018 respectively.

Table 3: Biot number and Quench severity of the bioquenchants

Quenchants	Medium carbon Steel	
	Biot Number	Quench severity(m^{-1})
Groundnut oil	0.029	6.140
Sheabutter oil	0.028	5.998
Jatropha oil	0.028	5.925
Palm kernel oil	0.024	5.212
Melon oil	0.022	4.710
Palm oil	0.019	4.142
Mineral oil	0.018	3.927

The Grossmann quench severity (H) was calculated from experimental data and the values obtained showed the quench severity of groundnut oil, sheabutter oil and jatropha oil has nearly the same, with a value of 6.0 m^{-1} Figure 5; while, palm oil and conventional mineral oil has the lowest quench severity of 4.0 m^{-1}.

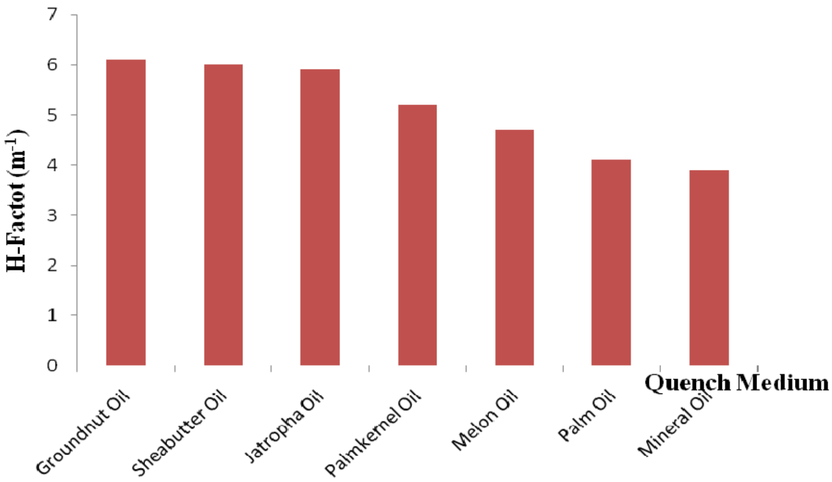

Figure 5. Grossman H-factor of various medium

However, palmkernel oil and melon oil has their quench severity values to be 5.2 and 4.7 m^{-1} respectively. The quench severities of the bioquenchants used was found to be directly related to the biot number, the higher the biot number the higher the quench severity. The quench severity of the bioquenchants followed this decreasing order.

Groundnut oil ≥ Sheabutter oil ≥ Jatropha oil > Palmkernel oil > Melon oil > Palm oil > Mineral oil.

CONCLUSIONS

Among the vegetable oils, highest heat transfer coefficients and cooling rate was obtained for jatropher oil while lowest heat transfer coefficient and cooling rate was obtained for palm oil. Higher heat transfer coefficient was found with lower viscosity oils and likewise the heat flux during quenching was influenced by the viscosity. In the entire bioquenchants, cooling rate was found to be strongly dependent on the viscosity of the quench oil and the saponification number.

Based on the heat flow parameters; palm oil, sheabutter oil, palmkernel oil and mineral oil can be used has slow quenching media; while, Jatropha oil, groundnut oil, melon oil may be used has fast quenching oil. The quench severities of the bioquenchants was directly related to the biot number, the higher the biot number the higher the quench severity.

Groundnut oil ≥ Sheabutter oil ≥ Jatropha oil > Palmkernel oil > Melon oil > Palm oil > Mineral oil.

The quench severity of the bioquenchants followed this decreasing order.

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