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HEAT TRANSFER COEFFICIENT CHARACTERIZATION OF VEGETABLE OILS[1]

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Abstract

Heat transfer coefficients of a quenchant are an important for evaluation of their potential use for the heat treatment of steel. Vegetable oils are of interest as potential replacements for petroleum oil-based quenchants. Therefore, it is of interest to determine the characteristic quenching performance, as characterized by heat transfer coefficients, of various vegetable oils of potential interest in the Brazilian heat treatment industry for use as replacements for petroleum quenching oils. This paper summarizes heat transfer coefficient characterization results obtained for five vegetable oils (cotton, canola, sunflower, corn and soybean) and two commercial petroleum oil-based quenchants (Microtemp 153B and Microtemp 157).

Keywords: Quenchant; Heat transfer coefficient; Vegetable oil; Cooling curve.

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INTRODUCTION

There have been various investigations on the use of vegetable oils and (animal oils) as quenchants. One of the earliest studies involving cooling curve and heat transfer analysis of quenching properties was conducted by Rose in 1940 with rapeseed oil.[1] Higher cooling rates were observed for rapeseed oil compared to petroleum oil which were attributed to the relatively poor stability of the vapor blanket formed by the rapeseed oil.[1]

Tagaya and Tamura subsequently compared the quench severity of different vegetable oils including: soybean, rapeseed and castor oils with mineral oils and fish/animal oils with respect to fluid source, viscosity and oxidative stability for various naturally derived fluids.[2] These data showed that although the Grossmann quench severity factors were comparable for both castor oil (H = 0.199) and soybean oil (H = 0.200), the cooling times from 700 to 300°C were significantly faster for castor oil than for soybean oil using a JIS K 2242 silver probe test which utilizes a 10 mm dia x 30 mm cylindrical silver probe with a surface thermocouple.[3]

Fujimura and Sato also studied the quenching performance of vegetable oils reported earlier by Tagaya and Tamura and also added castor oil to their study in addition to ethyl esters of oleic, palmitic and stearic acid *versus* different petroleum oil quenchants and concluded that the performance of soybean and rapeseed oil were essentially equivalent.[4] Quenching performance of the ethyl esters were also equivalent to each other and exhibited greater quench severity than the vegetable oils. Castor oil, however, was found to be thermally unstable. The quenching performance of castor oil was also studied by Farah, et. al.[5] and the thermal instability of this oil was subsequently confirmed.[6]

Currently, the most commonly cited vegetable oil basestocks used for quenchant formulation in the USA are based on canola oil,[7,8] and soybean oil.[9] Recently, a crambe oil based fluid has been reported as a potential quenchant.[10] Przylecka and Gestwa have reported the use of a vegetable oil-based quenchant for hardening carburized steels.[11]1

Prabhu studied the heat flux properties of palm oil[12] and extensive heat transfer and wetting studies of coconut, sunflower, groundnut, palm and castor oils.[12-15] With the exception of palm oil, these vegetable oils are not commonly considered as basestocks for quenchants in North and South America. Interestingly, with the exception of castor oil, relatively little difference in surface wetting properties were observed in Prabhu's work and quench severities comparable to a conventional, non-accelerated mineral oil were observed.

Totten, et. al. reported the results of cooling curve, hardening performance, heat transfer, and rewettability characterization studies conducted with crude and partially hydrogenated and winterized soybean oils[16] provided by Honary.[17] Because of the strong influence of the test specimen surface on the wetting behavior (and therefore on the quenching behavior), unalloyed (Ck 45) steel probes were used. This work provided

1 The specific product reported by Prezylecka and Gestwa was a commercial product designated as Bioquench 700 manufactured by Houghton International. In the USA, this product is based on canola oil (see References 17 and 56). However, in Poland, this product was reportedly based on rapeseed oil.

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a simultaneous examination of the martensitic transformation with local differences, and dependencies on the rewetting time (and dependencies on the metallurgical condition of the steel).

Cooling curve analyses showed that immersion quenching was primarily influenced by the sequence of the cooling phases and different heat transfer rates. Heat transfer on the specimen surface was primarily determined by the rewetting conditions and depended on the cooling characteristics of the quenching medium used, bath temperatures, and agitation rates. The soybean oils investigated showed no significant differences in cooling behavior and rewetting conditions on the test specimen surface and cooling rates were similar. Comparison of the cooling time-temperature and cooling rate curves showed that vegetable oils exhibited faster cooling rates than the mineral oil used as a reference. More recent results confirmed that vegetable oils not only exhibited faster cooling rates but also they exhibited nearly no full-film boiling behavior.[18]

The objective of this study was to compare the quenching performance using calculated heat transfer coefficients of a series of vegetable oils of greatest potential interest in Brazil as potential basestocks for quenchant formulation. These evaluations will utilize time-temperature data obtained from cooling curve analysis conducted according to ASTM D6200 for the calculation of heat transfer coefficients. Heat transfer coefficients will be calculated from the cooling curve data using a commercial inverse code.

EXPERIMENTAL

The vegetable oils used for this work were purchased at the local market in Sao Carlos, Brazil and were characterized and used in the as-purchased condition. The vegetable oils that were purchased included: canola oil, cottonseed oil, corn oil, sunflower oil, and soybean oil (commercially designated as "pure" soybean oil). Quenching performance of these oils was compared to two commercially available quenching oils: Micro Temp 157 (a conventional "slow" oil) and Micro Temp 153B (an accelerated "fast" oil).[2]

Cooling curves were obtained in the non-agitated condition at 60°C according to ASTM D6200 "Standard Test Method for Determination of Cooling Characteristics of Quench Oils by Cooling Curve Analysis" which utilizes a 12.5 mm dia x 60 mm INCONEL 600 cylindrical probe with a Type K thermocouple inserted to the geometric center. After heating the probe in a furnace to 850 °C, it was then manually and rapidly immersed into 2000 mL of the oil to be tested which was contained in a tall-form stainless steel beaker. The probe temperature and cooling times are recorded at selected time intervals to establish a cooling temperature versus time curve.

[2] The Micro Temp 157 and Micro Temp 153B were obtained from Micro Quimica Ind. Com. Ltda., Rua Projetada 225, Jardim União, 09970-000 Diadema – SP, Brazil: www.micro-quimica.ind.br.

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CALCULATION OF HEAT TRANSFER COEFFICIENTS

Heat transfer processes are complex and the heat transfer coefficient is a complex function of variables describing this process. Generally, the heat transfer coefficient is a function of the fluid flow, component (probe) shape and dimensions, temperature and physical properties of the liquid: thermal conductivity, specific heat capacity, density and viscosity. The heat transfer coefficient can be defined as the quantity of heat transferred per unit time per unit area of a surface when the difference of temperatures between the surface and liquid equals one degree absolute. Since quenching processes are actually heat transfer processes, the heat transfer coefficient is an excellent single parameter for quenchant characterization.

A commercial code designated as HT-MOD[3] (Heat Treating Modeling) which is a commercial code that is used to simulate heat treatment processes was used for this work.[19] This code is also used to calculate heat transfer coefficients as function of time by solving an inverse heat transfer problem. The model is based on a numerical optimization algorithm which includes a finite element module for calculating, with respect to time and space, the temperature distribution and its coupled micro-structural evolution. In this case, since an Inconel 600 probe was used that does not undergo microstructural phase transformation, only heat transfer coefficients were calculated using Equation 17. The boundary conditions are shown on Figure 1 and calculated using Equation 18.

$$\frac{1}{r}\frac{\partial}{\partial r}\left[rk\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right]+Q=c\rho\frac{\partial T}{\partial t} \qquad (17)$$

where:

T Temperature
K Thermal conductivity
c Specific heat.
ρ Density.

Q Heat source by enthalpies of phase transformations

$$-k\frac{\partial T}{\partial n}=h_i\left(T-T_{am}\right) \qquad (18)$$

[3] HT-MOD is a commercial code which is available from: KB Engineering S.R.L.; Florida 274, Piso 3, Of. 35 (1005) Buenos Aires – Argentina; Tel: (54-11) 4326-7542; Fax: (54-11) 4326-2424; Internet: http://www.kbeng.com.ar/en/.

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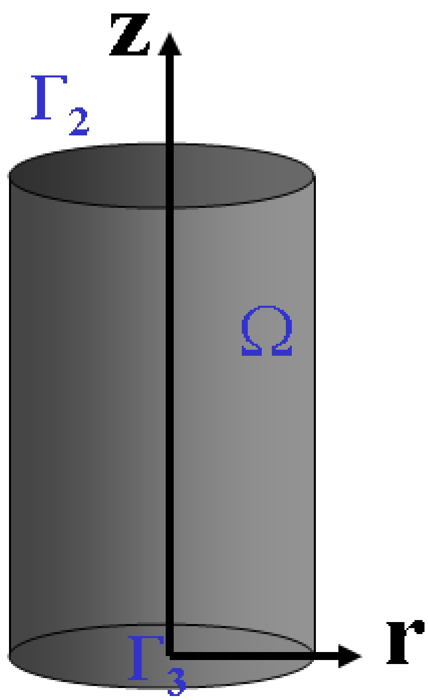

Figure 1. Boundary conditions for heat transfer coefficient calculation.

Calculations were performed using a finite element mesh containing 11 nodes along the radial direction and 21 nodes along the longitudinal direction. The discrete time variable of 50 seconds and 180 time steps were used. The total time of each process was divided into a sufficient number of time intervals where the linear variation of the heat transfer coefficient can be assumed.[20] The selection of the initial values for these coefficients and of the quantity and length of the time intervals was sample-dependent. The mean square difference between the measured and calculated temperatures obtained after optimization of the heat transfer coefficients was about 1°C. Figure 2 shows the calculated heat transfer coefficients as a function of the core temperature of the probe. The quenching performance of the vegetable oils used for this study was compared to two commercial petroleum oil quenchants: Microtemp 157, a conventional petroleum quench oil and Microtemp 153B, an accelerated petroleum quench oil.

RESULTS AND DISCUSSION

Cooling Mechanism Results

Petroleum oils typically exbibit a vapor film that surrounds the hot metal surface resulting in very slow full-film boiling. Such oils are designated as “slow” or “conventional” quench oils. However, quench oils are available that contain additives that destabilize the vapor film resulting in much shorter durations of full-film boiling and these oils are designated as “fast” or “accelerated” quench oils. At the Leidenfrost temperature, the vapor film ruptures and nucleate boiling results which is the fastest cooling mode. When the surface temperature decreases to approximately to the boiling point of the fluid, nucleate boiling ceases and slow cooling by convection results. This

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characteristic behavior is illustrated in Figure 2. Some researchers in this field estimate heat transfer over the temperature range of 700 °C - 450°C which is designated as the “boiling process range”.

Because of the relatively high molecular weight of the triglyceride structure of the vegetable oils, they do not boil under atmospheric pressure conditions. In fact, high vacuum conditions are required to obtain any substantial boiling of the more volatile fractions in a vegetable oil.[21,22] Therefore, typically, vegetable oils undergo thermal/oxidative degradation before boiling. Vegetable oils do not exhibit film boiling or nucleate boiling as shown in Figure 2. This is an important consideration when designing quenching processes utilizing vegetable oil-based fluids.

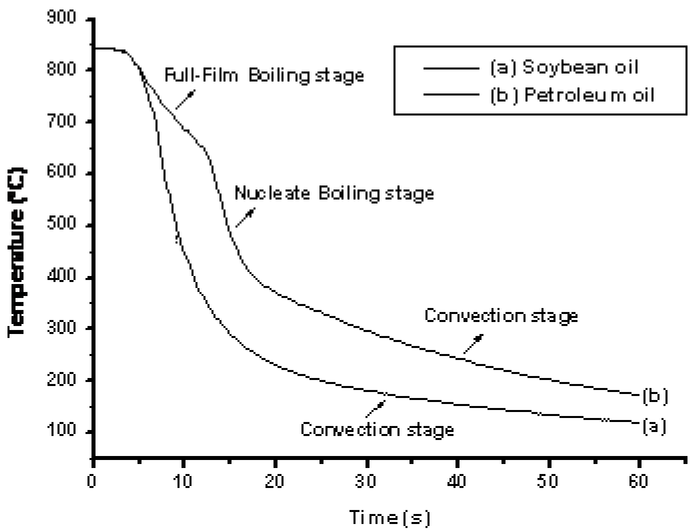

Figure 2. Comparative illustration of the different cooling mechanisms exhibited by petroleum oil and a vegetable oil. These cooling curves were obtained at 60 °C using the probe and procedure described in ASTM D6200 (no agitation).

Heat Transfer Coefficient Calculation Results

A plot of the heat transfer coefficients as a function of the centerline (core) temperature of the ASTM D6200 12.5 mm (dia) x 60 mm cylindrical Inconel 600 probe when quenched in the vegetable oils and two petroleum oils of this study are shown in Figure 3. These data were obtained using the commercial code discussed above. It is interesting to note that while both of the petroleum quench oils Microtemp 157 (T 157), an unaccelerated (slow) oil, and Microtemp 153B (T 153B), an accelerated (fast) oil exhibit full-film boiling, this is typically not observed for any of the vegetable oils evaluated in this study. As expected, the Microtemp 157 slow oil exhibited a longer full-film boiling duration than did the Microtemp 153B fast oil. Furthermore, the Microtemp 153B fast oil exhibited a significantly higher maximum heat transfer coefficient at a higher temperature than the Microtemp 157 slow oil and comparable to the vegetable oils evaluated.

Comparison of the *maximum* heat transfer coefficients exhibited by the vegetable oils in this study decreased as follows:

sunflower > corn > soybean > canola > cottonseed

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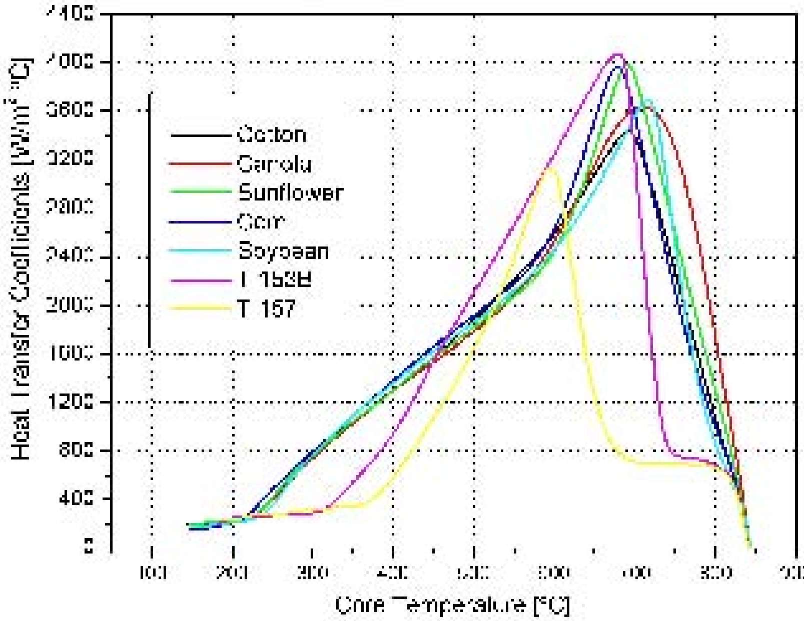

Figure 3. Heat transfer coefficient as a function of the centerline (core) temperature of the ASTM D6200 12.5 mm (dia) x 60 mm cylindrical Inconel 600 probe when quenched in a series of vegetable oils and two petroleum oils: Microtemp 157 (T 157), an unaccelerated (slow) oil and Microtemp 153B (T 153B), an accelerated (fast) oil.

Another method of comparing cooling properties of quenchants is to determine the heat transfer coefficients at 700°C and 450°C and then average them which provides a measure of cooling power through the boiling process range of oil and water-polymer solutions. Also these two temperatures have metallurgical significance in that 700°C approximates the pearlite transformation range of many steels and 450°C approximates the martensite start (Ms) temperature. Thus, the average heat transfer coefficient between 700°C - 450°C is a measure of the ability of a quenchant to harden steel. Therefore, the average heat transfer coefficient between 700°C - 450°C was determined for the quenchants evaluated in this study and the results are shown in Table 1.

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Table 1. Average heat transfer coefficients between 700°C - 450°C for different vegetable oils and two petroleum oil quenchants

Quenchant	Heat Transfer Coefficient[1] (W/m^{2}K)		
	700°C	450°C	Average Value[2]
Corn	3409	1652	2530
Soybean	3513	1617	2565
Cottonseed	3304	1565	2434
Canola	3565	1548	2556
Sunflower	3739	1565	2652
Microtemp 157 "Slow" Oil	696	1061	878
Microtemp 153B "Fast" Oil	3130	1548	2339

1. *These heat transfer coefficients were calculated using HT-MOD (see footnote 3)*
2. *The average value was calculated by: $[h_{700} + h_{450}]/2 = h_{ave}$*

The average heat transfer coefficients between 700°C and 450°C follow the order:

Microtemp 157 < Microtemp 153B < Corn < Soybean < Cottonseed < Canola < Sunflower

As expected, the "slow" petroleum oil (Microtemp 157) was much slower than all of the other quenchants which is undoubtedly influenced by the prolonged very slow cooling full-film boiling process. By destabilizing the vapor blanket formed around the hot metal surface, the average heat transfer coefficient of the boiling processes between 700°C and 450°C was increased considerably. However, all of the vegetable oils exhibited higher heat transfer coefficients than either petroleum oil quenchant with corn oil exhibiting the lowest average heat transfer coefficient in the region and sunflower oil exhibiting the highest average heat transfer coefficient.

CONCLUSIONS

The quenching performance of a series of vegetable oils was characterized by determining their heat transfer coefficients. Analysis of the data showed that all of the vegetable oils exhibited higher heat transfer coefficients relative to a commercial slow petroleum oil quenchant. When the petroleum oil quenchant was formulated with additives to destabilize the full-film boiling process, the maximum heat transfer coefficient was comparable to the fastest vegetable oil (sunflower oil) evaluated. Furthermore, these data show that each of the vegetable oils evaluated exhibits a different overall cooling process as indicated by their heat transfer coefficients.

Characterization of vegetable oils using heat transfer coefficients clearly showed that they do not exhibit a significant full-film boiling or nucleate boiling process and cooling was predominantly by convection. This is reasonable since vegetable oils do not readily boil under atmospheric pressure condictions (although they may degrade). As expected, the slow petroleum oil exhibited prolonged full-film boiling (very slow cooling) behavior whereas the so-called fast petroleum oil quenchant exhibited a much shorter duration of the full-film boiling process.

Taken together, these data clearly show that although vegetable oils, in general, exhibit interesting quenchant properties; they do not model those cooling properties exhibited by either fast or slow petroleum oil quenchants.

REFERENCES

1 Rose, A. Das Abkühlungsvermögen von Stahlabschreckmitteln. *Archiv.für das Eisenhüttenwesen*, 1940, Vol. 13, No. 8, p. 345-354.

2 Tagaya, M., Tamura, I., Studies on the quenching media 3rd report. The cooling ability of oils.*Technology Report, Osaka University*, 1954, Vol. 4, p. 305-319.

3 JIS K 2242-1980, "Japanese Industrial Standard – Heat Treating Oil".

4 Fujimura, Y., Sato, T., The composition of quenching oil and quenching effects, *The Iron and Steel Institute of Japan (ISIJ)*, 1963, Vol. 49, p. 1008-1015.

5 Farah, A.F., Crnkovic, O.R., Canale, L.C.F., Castor oil: Studies for heat treatment applications, in *19th Heat Treating Society Conference Proceedings,* Eds. S. Midea and G. Pfaffmann, ASM International, Materials Park, OH, 1999, p. 251-254.

6 Canale, L.C.F., Fernandes, M.R., Agustinho, S.C.M., Totten, G.E., Farah, A.F., Oxidation of vegetable oils and its impact on quenching performance, *Int. J. Materials and Product Technology*, 2005, Vol. 24, No. 1-4, p. 101-125.

7 Brennan, R.J., Faulkner, C.H., Massuda, D., A quenchant based on canola oil", *Advanced Materials & Processes*, August 1997, Vol. 152, No. 2, p. 32S – 32U.

8 Brennan, R.J., Faulkner, C.H. A new quenching alternative, in Totten, G.E., Funatani, K., Howes, M.A.H., Sjostrom, S. (Eds.), *Conf. Proceed. 2nd International Conference on Quenching and Control of Distortion*. ASM International, Materials OH, 1996, p. 423-428.

9 Honary, L.A.T., Performance of vegetable oils as a heat treat quenchant, in *Totten, G.E., Funatani, K., Howes, M.A.H., Sjostrom, S. (Eds.), 1996, Conf. Proceed. 2nd International Conference on Quenching and Control of Distortion*, ASM International, Materials OH, 1996, p. 595-605.

10 Lazerri, L., De Mattei, F. Bucelli, F., Palmieri, S., Crambe oil: A potentially new hydraulic oil and quenchant, *Ind. Lubr. Tribol*., 1999, Vol. 49, No. 2, p. 71-77.

11 Przylecka, M., Gestwa, W., The influence of Bio-Quench 700EU: Conditions on hardness of carburized components*, Inżynieria Materiałowa*, 2007, Vol. XXVIII, No. 3-4, p. 715-719.

12 Prabhu, K.N., Fernandes, P., Determination of wetting behavior, spread activation energy, and quench severity of bioquenchants, *Metallurgical and Materials Transactions B*, August 2007, Vol. 38, No. 4, p. 631-640.

13 Prabhu, K.N., Prasad, A., Metal/quenchant interfacial heat flux transients during quenching in conventional quench media and vegetable oils, *J. Mat. Eng. and Perf.,* 2003, Vol. 12, No. 1, p. 48-55.

14 Prabhu,K.N., Fernandes,P., Effect of surface roughness on metal/quenchant interfacial heat transfer and evolution of microstructure", *Materials and Design*, 2007, Vo. 28, p. 544-550.

15 Fernandes,P., Prabhu,K.N., Comparative study of heat transfer and wetting behaviour of conventional and bioquenchants for industrial heat treatment**",** *International Journal of Heat and Mass Transfer*, 2008, v 51, n 3-4, p. p 526-538.

16 Totten, G.E., Tensi, H.M., Lanier, K., Performance of vegetable oils as a cooling medium in comparison to a standard mineral oil", *J. Mat. Eng. and Perf*., 1999, Vol. 8, No. 4, p. 409-416.

17 Honary, L.A.T., Soybean based hydraulic fluid", *U.S. Patent 5,972,855*, October 26, 1999.

18 Ester Carvalho de Souza, Mauro R. Fernandes, Sylvana C.M. Augustinho, Lauralice de Campos Franceschini Canale, George E. Totten, "Comparison of Structure and

Quenching Performance of Vegetable Oils**",** J. ASTM International, 2009, Vol. 6, No. 9, Paper Number JAI 102188.

19 R.N. Penha, L.C.F. Canale, G.E. Totten, G.S. Sarmiento, "Simulation of Heat Transfer Properties and Residual Stress Analyses of Cooling Curves Obtained from Quenching Studies" J. ASTM International, 2006, Vol. 3, No. 5, Paper ID No. 13614.

20 Sarmiento, G. S.; Gastón, A.; Vega, J. "Inverse heat conduction coupled with phase transformation problems in heat treating process". COMPUTATIONAL MECHANICS - New Trends and Applications. E. Oñate and S.R. Idelsohn (Eds.). CIMNE, Barcelona, 1998. CD-Book. Part VI, Section 1, Paper 16.

21 P. Wentzel and P.S. Lammers, "Boiling Properties and Thermal Decomposition of Vegetable Oil Methyl Esters With Regard to Their Fuel Suitability", J. Agric. Food Chem., 1997, Vol. 45, No. 12, p. 4748-4752.

22 K.D.C. Hickman, "High-Vacuum Short-Path Distillation – A Review", Chem. Rev., 1944, Vol. 34, No. 1, p. 51-106.