Parallelized Particle Swarm Optimization to Estimate the Heat Transfer Coefficients of a Series of Vegetable Oils in Comparison with Typical Fast Petroleum Quench Oil Quenchant

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Abstract

An inverse solver for the estimation of the temporospatial heat transfer coefficients (HTCs), without using prior information of the thermal boundary conditions, was used for immersion quenching into a series of vegetable oils and two commercial petroleum oil quenchant. The Particle Swarm Optimization method was used on near-surface temperature-time cooling curve data obtained with the so-called Tensi multi-thermocouple 12.5 mm diameter x 45 mm Inconel 600 probe. The fitness function to be minimized by a particle swarm optimization (PSO) approach is defined by the deviation of the measured and calculated cooling curves. The PSO algorithm was parallelized and implemented on a Graphics Processing Unit architecture. This paper describes in detail the PSO methodology to compare and differentiate the potential quenching properties attainable with a series of vegetable oils including: cottonseed, peanut, canola, coconut, palm, sunflower, corn and a soybean oil vs a typical accelerated petroleum oil quenchant.

Keywords: quenchant, heat transfer coefficient, particle swarm optimization, vegetable oil, petroleum oil

Introduction

Vegetable oils and animal oils have been used as quenchants for metals for thousands of years; however, historically, very little is known about quenching selection and practice from the period prior to 800 AD to approximately 1500 AD [1]. Eamon described various methods used to quench iron and steel during this time [2]. Although cold water was a common quenchant, it reportedly cause brittle steel problems. Reportedly, these problems could be solved by mixing water and various animal and plant materials to make an “oily” or “pulpy” quenching bath. Examples included: quenching scythes in suet, files in linseed oil and goat’s blood, quarry hammers in the juice of crushed caterpillars and the edges of steel cutting tools into a composition containing 1 part each of: radishes, horseradish, earthworms or larvae, and billy goat’s blood when the goat is in a “rut” -a quenching recipe reported to originate from the time of Pliny the Younger:61– ca. 112 AD [2]). It has recently been shown these anecdotal references would not be effective steel quenchants [3]. There are many more recent historical references detailing the successful use of vegetable oils and animal oils to harden steels [4]. Tawara and Tamura provided the first comparative structure-performance studies of a series of vegetable and animal oils on their relative ability to harden various steels [5,6]. However, although Tawara and Tamura’s work was based on cooling curve analysis, they did not specifically examine the use of heat transfer coefficients to characterize quenching performance.

Various works have been reported describing the use of Heat Transfer Coefficients to characterize the relative ability of a quenching medium to harden steel. Examples include the works of Russell [7] and Rose [8]. Rose reported that although cooling rate curves versus temperature completely and accurately describe the cooling capacity of quenchants, measured cooling rates also depend on the size, shape, and thermal properties of the steel. To quantify the cooling properties of a quenchant that are independent of the testing conditions, Rose proposed deriving the heat transfer coefficient from the cooling rate data obtained from cooling curve analysis assuming that the
temperature being measured within the probe used to obtain the cooling curves is equivalent to the interfacial temperature at the probe surface/quenchant interface which could be described by the Eq(1):

\[
\frac{dq}{dt} = \alpha(T_P - T_C)
\]

where:
\(\alpha\) is the Heat Transfer Coefficient,
\(T_P\) is the temperature of the probe,
\(T_C\) is the temperature of the quenchant,
\(A\) is the surface area of the probe, and
\(Q\) is the amount of heat transferred and is assumed equal to:

\[
Q = T_PGC
\]

Using this simplified calculation for \(\alpha\), Rose constructed quantified the cooling capacities of various quenchants obtained from heat transfer coefficients at 500°C, which was the temperature of the fastest transformation rate for most grades of steel available at that time (about 1940) [8]. However, Rose’s methodology, while relatively simple to perform, does not account for the varying heat transfer coefficient occurring on the steel surface throughout the quenching process.

More recently, Otero [9] and Kobasko [10] have reported heat transfer coefficient values for various vegetable oils which were obtained using a “simplified” computational method [10,11]. Although relatively easy to perform, this method does not readily produce vitally important continuous heat transfer profiles for a quenching medium throughout the cooling process. Such data is much more readily obtained by using an inverse method to solve the heat transfer problem such as the Finite Element Methods (FEM) utilized by many workers including recent studies involving vegetable oils reported by Kobasko [10], Carvalho [12], Jagannesh [13] and Ramesh [14] and others who have utilized Finite Element Methods (FEM).

For much of the more recently reported work a 12.5 mm diameter x 60 mm INCONEL 600 cylindrical probe with a Type K thermocouple inserted to the geometric center was used as the probe for temperature-time data acquisition of the quenching process. However, Kobasko and Liscic provided an extensive summary of the relative disadvantages of using such a probe when characterizing the heat transfer properties of various quenching media in the heat treat shop [15].

Liscic and co-workers have successfully utilized a larger cylindrical probe of 50mm diameter x 200 mm to effectively characterize actual heat transfer properties of quenching media under actual workshop conditions. The thermocouples (TCs) are positioned so that only radial heat flow is measured which is a prerequisite for a 1D heat-transfer calculation. The outer TC (the measured data of which are used as input for heat-transfer calculations) is placed at 1mm below the surface to assure minimum damping effect of transient surface temperatures. Two additional thermocouples are placed at the center and mid-radius on the same plane as the near-surface thermocouple. This probe is an essential component of the heat transfer “Gradient Method” utilized by Liscic to calculate the heat transfer properties of quenching media [16]. Recently, Liscic’s Gradient Methodology was used to calculate heat transfer performance of canola, coconut, corn, cottonseed, palm, peanut, soybean, sunflower oils and for comparison with a fast petroleum oil quenchant [17].

Many FEM Methods used to determine heat transfer properties involved during the quenching (hardening) process are solving as an ill-posed inverse problem originally proposed by Beck [18]. An inverse problem means that some of the initial, boundary conditions or material properties are not fully specified as determined from the measured temperature profiles at some specific locations. Solutions of the inverse problem are very sensitive to measurement errors, i.e. small errors in the measured data values can produce very large uncertainty in the solution. In general, the exclusivity and stability of an inverse problem solution is not guaranteed.

Inverse problems have been studied extensively due to their applications in various engineering disciplines. Most of the methods approach the Inverse Heat Conduction Problem (IHCP), as an optimization problem, i.e. the problem is defined as the minimization of a cost function or a fitness function measuring the distance between measurements and predictions [19, 20]. With the improvement of computer capability, a variety of numerical techniques and computational methods have been developed to provide accurate solutions for IHCP in the last decade. Among these methods, stochastic optimization methods have become a popular means of solving inverse problems, due to their capability of finding the global optimal result without computing the complicated gradient of the objective function.

Genetic algorithms have been used successfully for solving many types inverse heat transfer problems [21-22]. The quantitative evaluation of different numerical optimization techniques showed that stochastic methods could serve more accurate results for IHCP than gradient approaches in recovering complex thermal boundary conditions [23]. The Particle Swarm Optimization (PSO) algorithm became popular in the recent years due to its ability of maintaining a good balance between the convergence and diversity. Additionally, it has been shown that PSO can reduce the stability problems of the classical methods, for solving the inverse heat conduction problems [24,25,26].

In this work, a PSO optimization methodology will be used to facilitate the calculation of HTC's for a series of vegetable oils for subsequent comparison obtained under the same quenching conditions for a typical accelerated (fast) petroleum quenching oil. Included in this discussion will be a numerical overview of PSO compared with more conventional numerical methods.
used to determine Heat Transfer Coefficients under laboratory quenching conditions. This discussion will provide the algorithms required to apply this methodology to other quenching problems. A similar preliminary study was reported earlier for a palm oil and canola oil comparison [27]. The purpose of this work is to apply this methodology to a larger series of vegetable oils including cottonseed, peanut, canola, coconut, palm, sunflower, corn and a soybean oils.

**Experimental**

The vegetable oils used for this work included: cottonseed, peanut, canola, coconut, palm, sunflower, corn and a soybean oil were purchased at the local market in Sao Carlos, Brazil and were used as-purchased condition without the addition of antioxidants. Quenching performance of these oils was compared to a commercially available quenching oil: HoughtoQuench KM (an accelerated “fast” oil).

Cooling curves were obtained under unagitated conditions according ASTM D6200-01 - Standard Test Method for Determination of Cooling Characteristics of Quench Oils by Cooling Curve Analysis - at bath temperatures of 60°C with NO agitation [28]. However, instead of the standard 12.5 mm diameter. X 60 mm cylindrical INCONEL 600 assembly specified in D6200, a multiple thermocouple probe assembly (Tensi probe) shown in Figure 1 was used. After heating the Tensi probe in a furnace to 850°C (1562°F), 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 cooling temperature and cooling times were obtained at a data acquisition rate of 8 Hz and saved on disk storage and used to establish a cooling temperature versus time curve. (This temperature-time data file was also used for the MATLAB computational work described below.)

**Prediction of Heat Transfer Coefficients**

The IHCP method is based on temperature signals acquired during the process to be analyzed. The temperature is given by measurements at p points in the solid region, located at rk, (k=1…p) positions inside of the workpiece. On calling Tc,k, the measured temperatures, and Tc, the calculated temperature at those points, the solution of the inverse heat conduction problem can be obtained by minimizing the objective function Eq(4)

\[ S = \sum_{k=1}^{p} (T_{c,k} - T_{m,k})^2 = \min \]

The sample temperatures Tc,k are obtained by numerical simulation using the following assumptions. A two-dimensional axis-symmetrical heat conduction model is considered to predict the temperature field in a cylindrical work piece (the radius and length of the cylinder is noted by R and Z according to Fig 2). The HTC(z,t) function is considered on all the surfaces of the cylinder as functions of time and the
longitudinal local coordinate. Both the thermal conductivity, density and the heat capacity are varying with the temperature, k(T), ρ(T) and C_p(T). The temperature field is estimated by solving the Fourier equation of Heat Transfer, Eq(5):

$$\frac{\partial}{\partial t}\left( k \frac{\partial T}{\partial r} \right) + \frac{k}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + q_r = \rho(t)C_p \frac{\partial T}{\partial t}$$

(5)

with the initial and the boundary conditions

$$T(r, z, t = 0) = T_0$$

(6)

$$k \frac{\partial T}{\partial z} \bigg|_{z=r} = HTC(z,r)\left[T_q - T(r, z, t)\right]$$

(7.1)

$$k \frac{\partial T}{\partial z} \bigg|_{z=0} = HTC(z=0, r)\left[T_q - T(r, z, t)\right]$$

(7.2)

$$k \frac{\partial T}{\partial z} \bigg|_{z=r} = HTC(z=r, r)\left[T_q - T(r, z, t)\right]$$

(7.3)

Figure 2: The geometry and the Boundary Conditions of the work piece.

where r and z is the local coordinate, t is the time, T_0 stands for the initial temperature and T_q is the temperature of the cooling medium and q_r stands for the latent heat. (Because there is no latent heat generation during the experiments, the value of q_r is always equal to zero).

For the prediction of the HTC functions occurring during immersion quenching, the objective function Eq (4) has been minimized by using the PSO algorithm. The basic PSO model consists of a swarm of M particles moving in the search space. Each particle is a potential solution of the global optimum. In other words, each particle stands for a set of input parameters by its position (X_i) which could give the lowest fitness value (the global optimum) in the search space. For a N-dimensional search space, the position of the i^th particle is represented as X_i = (x_{i1}, x_{i2}, . . . , x_{iN}). For each generation, the new particle position is found by adding a displacement to the current position where the displacement is the particle velocity multiplied by a time step of one as shown in Eq. (8)

$$X^{n+1} = X^n + V^{n+1}$$

(8)

In Eq. (8), X^n and X^{n+1} represent the previous and current positions of particle i, V^{n+1} is the current velocity of particle i and is represented as V^{n+1} = (v_{i1}, v_{i2}, . . . , v_{iN}). The velocity of each particle is also updated for each generation and is given by Clerck [30]:

$$V^{n+1} = C_1 V^n + C_2 (P_{best,i} - X^n) + C_3 \varepsilon_2 (G_{best} - X^n)$$

(9)

where V^n and V^{n+1} are the previous and current velocities of the particle i, respectively. Each particle maintains a memory of its previous best position, i.e. P_{best,i} = (p_{i1}, p_{i2}, . . . , p_{iN}), where the position giving the best fitness function value. The best position among all the particles in the swarm is represented as the global best position, i.e. G_{best} = (p_{g1}, p_{g2}, . . . , p_{gN}). The new velocity in Eq. (9) can be seen as the sum of three parts. The constant multiplier C_3 was set to 0.7298 and C_1 and C_2 were equal to 2.05. The computational steps of the PSO algorithm described above are given as follows:

- Step 1: Generate the initial particles in a swarm by randomly generating the position and velocity for each particle.
- Step 2: Evaluate the fitness function of each particle.
- Step 3: Update the Pbest,i for each particle, if its fitness is smaller than the fitness of its previous best position (P_{best,i}).
- Step 4: Update the Gbest, if the fitness function of a particle is smaller than the fitness of the best position of all particles (G_{best}).
- Step 5: Update each particle according to Eqs. (5) and (7).
- Step 6: Repeat the loop until the stopping criteria or a predefined number of generations is reached.

The applied algorithm has been implemented to Graphic Accelerator (General Purpose Graphic Card) which significantly increased the computational efficiency.

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Results and Discussion

Cooling Curve Analyses Results

The cooling time-temperature curves for cottonseed, peanut, canola, coconut, palm, sunflower, corn and a soybean oils and a typical fast petroleum oil, Houghtoquench HKM, for all four positions of the Tensi probe indicated shown in Figure 1 are provided in Figures 2 a-d and the corresponding cooling rate curves for these oils are shown in Figures 3a-d respectively. All cooling curves were obtained at 60 °C in an unagitated condition according to ASTM D6200 [28]. The standard cooling parameters for the center thermocouple location are summarized in Table 1. Comparing the cooling curves shown in Figure 2 and Figure 3, for palm oil versus canola oil, it is
evident that palm oil exhibited an apparent, but relatively short, film boiling region whereas, if film boiling actually occurred in canola, cottonseed, soybean, peanut and sunflower oils, it was of comparatively short duration. This behavior suggests the presence of an as-yet unidentified more volatile component in the palm oil. The surface cooling curves closest to the bottom end of the Tensi probe exhibited the fastest cooling as would be expected due to the well-known end-cooling effect. However, the other surface cooling curves were relatively similar to each other which would be consistent with very similar and relatively uniform heat transfer behavior compared to what would be expected for a vaporizable quenchant such as a petroleum quench oil.

The cooling time-temperature curves for Houghtoquench HKM is shown in Figure 2i the cooling rate curves are shown in Figures 3i. As expected, Houghtoquench HKM exhibited a pronounced film boiling region. Interestingly, all three surface cooling curves are clearly distinguishable relative to the vegetable oil curves and which illustrates a moving wetting front, in this case, from bottom upward along the Tensi probe surface. This is a normal and expected behavior for vaporizable quenchants. However, when contrasted with the vegetable oil curves, the data suggests much uniform surface cooling for the vegetable oils.

Probe centerline cooling parameters summarized in Table 1 shows that the vegetable oils cool faster than either petroleum oil quenchant with a comparatively shorter film boiling duration. However, the maximum cooling rate was lower for the vegetable oils, although it occurred at a somewhat higher temperature relative to Houghtoquench HKM, a fast (accelerated) petroleum quench oil.

Figure 2: a – Cooling time-temperature curve for palm oil at 60°C, no agitation (using Tensi probe). b – Cooling time-temperature curve for canola oil at 60°C, no agitation (using Tensi probe).

Figure 2: c – Cooling time-temperature curve for coconut oil at 60°C, no agitation (using Tensi probe). d - Cooling time-temperature curve for corn oil at 60°C, no agitation (using Tensi probe). e - Cooling time-temperature curve for cottonseed oil at 60°C, no agitation (using Tensi probe). f - Cooling time-temperature curve for peanut oil at 60°C, no agitation (using Tensi probe).
Figure 2: g – Cooling time-temperature curve for: g- soybean oil; h - sunflower oil; i - Houghtoquench HKM petroleum oil (fast quench oil). At 60°C, no agitation (using Tensi probe).

Figure 3: a - Cooling rate curve for palm oil at 60°C, no agitation (using Tensi probe). b - Cooling rate curve for canola oil at 60°C, no agitation (using Tensi probe).

Figure 3: c - Cooling rate curve for coconut oil at 60°C, no agitation (using Tensi probe). d - Cooling rate curve for corn oil at 60°C, no agitation (using Tensi probe).
plots of heat transfer with the coordinates of heat transfer coefficient, elapsed time upon immersion and at the near-surface thermocouple position of 11.5 mm of the Tensi probe are shown in Figures 4 and 5. This thermocouple position was selected because it is the position where the maximum heat transfer coefficient was observed for the different oils examined.

![Figure 3: e - Cooling rate curve for cottonseed oil at 60°C, no agitation (using Tensi probe). d - Cooling rate curve for peanut oil at 60°C, no agitation (using Tensi probe). g - Cooling rate curve for soybean oil at 60°C, no agitation (using Tensi probe). h - Cooling rate curve for sunflower oil at 60°C, no agitation (using Tensi probe). i - Houghtoquench HKM petroleum oil (fast quench oil).](image)

**Figure 3:** e - Cooling rate curve for cottonseed oil at 60°C, no agitation (using Tensi probe). d - Cooling rate curve for peanut oil at 60°C, no agitation (using Tensi probe). g - Cooling rate curve for soybean oil at 60°C, no agitation (using Tensi probe). h - Cooling rate curve for sunflower oil at 60°C, no agitation (using Tensi probe). i - Houghtoquench HKM petroleum oil (fast quench oil).

### Heat Transfer Coefficient Results

Table 2 summarizes the heat transfer coefficient (maximum) variation with each near-surface thermocouple position of the Tensi probe (Figure 1) as calculated by the particle swarm computational methodology. The 3D heat transfer coefficient plots of heat transfer with the coordinates of heat transfer coefficient, elapsed time upon immersion and at the near-surface thermocouple position of 11.5 mm of the Tensi probe are shown in Figures 4 and 5. This thermocouple position was selected because it is the position where the maximum heat transfer coefficient was observed for the different oils examined.

**Table 1:** Cooling parameters obtained by ASTM D6200 at 60 ºC bath temperature and with no agitation. These data are from the center thermocouple position only.

<table>
<thead>
<tr>
<th>Vegetable oils</th>
<th>Petroleum -based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canola</td>
<td>3.8</td>
</tr>
<tr>
<td>Coconut</td>
<td>5.1</td>
</tr>
<tr>
<td>Corn</td>
<td>4.4</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>2.7</td>
</tr>
<tr>
<td>Palm</td>
<td>6.6</td>
</tr>
<tr>
<td>Peanut</td>
<td>3.1</td>
</tr>
<tr>
<td>Soybean</td>
<td>3.7</td>
</tr>
<tr>
<td>Sunflower</td>
<td>3.4</td>
</tr>
<tr>
<td>HKM (Fast)</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 4a shows that palm oil exhibits a pronounced film boiling behavior as observed for both the cooling time-temperature (Figure 2a) and cooling rate (Figure 3a) curves. Maximum heat transfer occurs at progressively longer times indicating an upward movement of the boiling front with respect to time. The largest magnitude of the maximum heat transfer transition was greatest (3537 Wm⁻²K⁻¹) at the 11.25 mm surface position of the probe.

The remaining vegetable oils, on the other hand, shown in Figure 3, shows much shorter duration of film boiling and while the maximum heat transfer did progress in an upward movement along the surface of the probe, the total time for cooling to occur was shorter than the results exhibited by palm oil. It is important to note that as opposed to the behavior observed for palm oil, maximum heat transfer occurred at nearly the same time for the 11.25 and 22.5 mm surface thermocouple positions indicated much more uniform heat transfer. Furthermore, the magnitude of the maximum heat transfer at the 11.25 mm surface position of the probe which is...
the same position where the maximum heat transfer occurred, (11.25 mm thermocouple position) the for palm oil.

The heat transfer behavior of the “fast” petroleum oil quenchant HKM shown in Figure 4c exhibited similar behavior as observed for palm oil (Figure 4a). As expected, since petroleum oils do characteristically exhibit significant film boiling behavior this is observed by the film boiling behavior indicated and that the rewetting front traverses in an upward axial motion along the surface of the probe. Maximum magnitude of the HKM (5714 Wm⁻²K⁻¹), as with palm oil occurred at the 11.25 mm surface probe position. This was the largest heat transfer coefficient of any of the oils evaluated in this study.

While these data are consistent with the information that is attainable with the cooling time-temperature curves (Figures 2) and cooling rate curves (Figures 3), the heat transfer coefficient curves provide a simpler quantitative characterization of quenching behavior.

Table 3 – Heat transfer coefficient (maximum) variation with the near surface thermocouple position of the Tensi probe (Figure 1) as calculated by the particle swarm computational methodology

<table>
<thead>
<tr>
<th>Quenchant</th>
<th>Max. Heat Transfer Coefficient (Wm⁻²K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>z = 2 mm</td>
</tr>
<tr>
<td>Canola Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>2083</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.5</td>
</tr>
<tr>
<td>Coconut Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1460</td>
</tr>
<tr>
<td>Time (s)</td>
<td>4.0</td>
</tr>
<tr>
<td>Corn Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1915</td>
</tr>
<tr>
<td>Time (s)</td>
<td>4.0</td>
</tr>
<tr>
<td>Cottonseed Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1006</td>
</tr>
<tr>
<td>Time (s)</td>
<td>0.0</td>
</tr>
<tr>
<td>Palm Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1832</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.4</td>
</tr>
<tr>
<td>Peanut Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1376</td>
</tr>
<tr>
<td>Time (s)</td>
<td>2.0</td>
</tr>
<tr>
<td>Soybean Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>1896</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.0</td>
</tr>
<tr>
<td>Sunflower Oil</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>2024</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.0</td>
</tr>
<tr>
<td>Houghtoquench HKM</td>
<td>HTC</td>
</tr>
<tr>
<td></td>
<td>2706</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Figure 4: 3-D Plots of heat transfer coefficients as a function of time for each of the three near-surface thermocouple positions for the Tensi probe (Figure 1) quenched at 60°C with no agitation obtained by the particle swarm computational method into a) palm oil; b) canola oil; c) Houghtoquench HKM.
method into a) coconut oil; b) corn oil; c) cottonseed oil; d) peanut oil; e) soybean oil; f) sunflower oil.

Figure 6 provides a comparative illustration of the surface heat transfer coefficient as a function of surface temperature for a 15 mm Inconel 600 cylindrical probe quenched into the vegetable oils and a fast petroleum quench oil (HKM) at 60°C under unagitated conditions. The results show that the fast petroleum quenching oil (HKM) exhibited the highest $ HTC_{\text{max}} $ at the highest surface temperature. It is important to note that although the HKM oil exhibited the highest $ HTC_{\text{max}} $ substantial film boiling behavior occurred as well. The $ HTC_{\text{max}} $ of the vegetable oils were similar in magnitude and occurred at similar surface temperatures but less than that exhibited by the HKM petroleum oil. However, the data shows a considerably longer film boiling duration for palm oil than exhibited by the other vegetable oils studied.

Figure 6: Heat transfer coefficient as a function of surface temperature at the 15 mm surface thermocouple position of the Tensi probe (Figure 1) quenched into canola oil, palm oil, coconut oil, corn oil, cottonseed oil, peanut oil, soybean oil, sunflower and a fast petroleum quench oil (HKM) at 60°C under unagitated conditions.

CONCLUSIONS

Cooling curve analysis and heat transfer characterization of two vegetable oils, canola oil and palm oil, which were used in the as-purchased condition, was performed. This work was performed using the so-called “Tensi” probe, an Inconel 15 mm diameter x 45 mm cylindrical test specimen equipped with three near-surface thermocouples and one center thermocouple. The cooling curve data showed that compared to the remaining vegetable oils studied, palm oil exhibited significant film boiling behavior as apparent in its cooling time-temperature profile whereas the other vegetable oils used for this study exhibited little, if any, apparent film boiling behavior. The other cooling curve parameters evaluated were approximately comparable. It is important to note that the rewetting behavior properties suggested by the surface cooling curves indicated that, with the exception of palm oil, it would be expected that vegetable oils, in general, would exhibit the relatively uniform quenching behavior compared to that behavior exhibited by the petroleum oil quenchant. However, although this would be expected to result in lower cracking and more uniform
distortion propensity, this was not specifically evaluated as part of this project.

Heat transfer coefficients were determined using a particle-swarm computational method discussed in detail herein. The results obtained essentially mirrored the conventional cooling time-temperature and cooling rate curves, however, the numerical data and graphical output provided a comparatively simpler and more relevant characterization overview than that provided by conventional cooling curve parameterization methods currently in use.

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