Experimental study of cooling characteristics to analyse quenching phenomenon of non-heat treatable material with different quenchants

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Abstract: Quenching is one of the commonly used process to improve mechanical properties for any materials. The quality of quenching and efficiency are usually measured by using various quench probes and get the cooling curves. The main parameters which are affecting the cooling characteristics are, geometry, quenchant type and materials grade, etc. A mathematical model that can be employed to get heat flux and cooling curves for a different materials/cooling medium combination. Present model coupled with nonlinear unsteady heat transfer with phase change, which leads to cooling curves for different materials/quenchant. Experiments are conducted in the standard laboratory condition to determine heat flux and surface temperature at the mid-plane of a 10 mm diameter by 70 mm long specimen of Stainless Steel material. InverseSOLVER software is used to analyse the experimental data to obtain cooling curves. This specimen is cooled with different quenching medium, such as, water, vegetable oil and different grade of lubricating oils. The experimental results are analysed for different quenchants using Inverse solver. The experimental results indicated that cooling curves, cooling rate, and the surface heat flux vary with quenchants.

1. Introduction

Immersion quenching is commonly used in heat treatment processes for obtaining martensitic and bainitic steels. The probes made are of standard material example stainless steel various grades of stainless steel can be used the quenching properties vary according to the grade therefore a probe made of standard material is used in the process for all the quenchants. A cooling curve is the graph obtained by plotting the measured temperature of materials with respect to time at geometric centre of cylindrical specimen when it is subjected to quenching process.

Most of the researchers have done work on quenching process but they have studied the material properties there are very few works on the thermodynamic properties so this is our field of interest.
The estimation of cooling rate, hardness, microstructure distribution for steel grade material during quenching process is done with the help of reference quench probe [1]. The measuring equipment was specially developed in order to compute the cooling rate of different quenchants [2]. Standard reference quench probes are used to determine the quality of quenchant. The important parameters like steel grade, bath temperature, thickness are effects the cooling curves. Different phase change phenomena as a function of temperature were determined using JMatPro software [3]. The polymer solution, water brine solution, and Mineral oil are employed as quenchants of different thermophysical properties, The standard ISO /DIS 9550 quench probe is employed to compute the cooling rate [4]. The quenching performance was evaluating heat transfer coefficient variation at different times after it is subjected to to an accelerated thermal-oxidation aging test [5]. The microstructure of quenched specimens is studied by optical microscope [6]. The cooling rate of quenchant is analysed of commercial quench oil MT650 [7]. To determine time dependent heat flux of stainless steel, function specification method is used at unknown boundary. The present formulation did not consider the magnitude of latent heat due to austenite decomposition.

The objective of this paper is to compute the heat flux variation of stainless steel, to analyze the cooling rate, to determine the convective heat transfer coefficient during Quenching processes and to understand the physics of boiling during Quenching process.

2. Material selection

Experiments are performed for stainless steel specimen and quenchants as water, vegetable oil, Castrol 4T and 2T oils at room temperature and their corresponding chemical composition, properties of material and Quenchants as shown in Table.1, 2 and 3 below.

| Table 1. Chemical Composition of Stainless Steel (304) |
|---------------------------------|
| Composition | C | Mn | Si | P | S | Cr | Mo | Ni | N   |
| %         | 0.08 | 2.0 | 0.75 | 0.045 | 0.030 | 18.0±20.0 | - | 8.0-10.5 | 0.10 |

| Table 2. Properties of Stainless Steel Material. |
|---------------------------------|
| Density | 8.03 g/Cm³ |
| Thermal Conductivity | 16.3 W/m-K |
| Melting range | 1399-1454°C |

| Table 3. Properties of Quenchants |
|---------------------------------|
| Water | Sunflower Oil | Castrol Activ 4T Oil | Castrol Go 2T Oil |
| Density (kg m⁻³) | 1000 | 917 | 0.8913 | 0.8737 |
| Viscosity at 25°C (cP) | 0.890 | 28.56 | 122.80 | 51.9 |
| Thermal Conductivity at 22°C W/m-K | 0.606 | 0.606 | >185 | 119 |
| Flash point (°C) | 314 | | | |
| Flash Point(°C) | | | | |
3 Experimental procedure
The Unique quench probe was used for the experiment. Which includes Electric resistance Furnace, probe, K-Type thermocouple, Quenchant, Data acquisition system, quenchant vessel and the vessel holding stand as shown in Figure. 1. The stainless steel specimen of 10 mm diameter and 70 mm long and this specimen is heated up to 850°C in electric resistance. The K-type Thermocouple is fitted in the probe further connected to data acquisition system. The vessel contains the quenchant having volume of 2 litres when the specimen is heated to the required temperatures it is dipped into the quenchant and the temperature changes with respect to time are observed and recorded with the help of data acquisition system. Also different quenchants are used for the experiment such as, distilled water, vegetable oil, two varieties of engine oil.

![Figure 1](image_url)

**Figure 1** An experimental overview to measure the Temperature-time data during quenching

3.1 Inverse Heat Conduction Including Source Term
The boiling heat transfer phenomena during quenching process was analysed for cylindrical geometry using cylindrical coordinate system; assuming symmetry with respect to axis, heat flux at the boundary treated as an unknown parameter. The heat transfer variation in the specimen while quenching was analyzed by the following equations:

\[
\frac{k}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T(r,z,t)}{\partial r} \right) + k \frac{\partial^2 T(r,z,t)}{\partial z^2} + \dot{q} = \rho c \frac{\partial T(r,z,t)}{\partial t} \tag{1}
\]

Initial conditions are, at \( t=0 \), \( T(r,z,t) = T_{\text{soak}} \).

The boundary conditions are,

\[-k \left( \frac{\partial T}{\partial z} \right) = 0 \text{ at } S_2, \quad -k \left( \frac{\partial T}{\partial r} \right) = q(t) \text{ at } S_1; \quad T \mid_{r=r_0} = T_{\text{max}}(t) \text{ at } t=0; \quad \text{end.} \]

Where
- \( C \) = Specific heat (J/kg K), \( K \) =Thermal conductivity (W/m K), \( r \) =Radial coordinate (m), \( S \) = Objective function (K), \( s \) = No. of thermocouples, \( T \) = Temperature (K), \( t \) = Time (s), \( z \) = Axial coordinate (m), \( \rho \) = Density (kg/m³).
4. Results and discussion

4.1 Cooling Curve Analysis
The temperature variation is recorded by thermocouple, which is fixed at centre of the stainless steel specimen. These temperature variations with time data, recorded during quenching, are used as input to the Inverse Solver. From Figure 2 it observed that the actual cooling path of the sample is decrease with temperature with respect to time. There are intersecting points at 295°C for water and vegetable oils, 525°C for water, lubricating 2T and 4T oil.

4.2 Computed Surface Cooling Rate
The variation of cooling rate for Stainless steel material with different quenchants as shown in Figure 3. During heating condition, the material is completely austenitic having same thermal characteristics. Once austenite decomposition starts, different magnitude of latent heat will be generated in the specimen. The thermal properties also differ across the specimen cross section. The total effect of this is observed on the cooling rate curves as being distinct for the specimen below the Ae3 (Temperature at which α ferrite austenite can exits equilibrium) temperature. The maximum cooling rates variation for this specimen are at 170°C/s, 75°C/s, 59°C/s, 55°C/s, at a temperature of 425°C , 655°C, 582°C, 496°C for distilled water, vegetable oil, lubricating 4T oil and 2T oil respectively.

4.3 Surface Heat Flux Curve Analysis
Figure 4 shows the surface heat flux was determined by using Equation 1. The stainless steel specimen is quenched in distilled water, vegetable oil, lubricating oil 4T and 2T. It is observed that the physics of the heat flux curves follows the same nature of the surface cooling rate curves in all the cases. The rate of heat energy removed from the solid is equal to the heat gain by the fluid during quenching, this is result of energy balance. Heat transfer within the solid specimen is purely by conduction, whereas heat transfer process between fluid and solid surface by convection. Here convection heat transfer process is extremely complicated due to two phase flow heat transfer. So there is boiling heat transfer which includes various regimes such as, nucleate boiling, vapor phase and the convection phase with time. This phenomenon of heat transfer depending on the surface temperature. The stainless steel material
releases the heat with respect to time is highly complicated and non-linear; this is because of phase transformation, also which is depending on cooling rate. The maximum heat fluxes are \(19.05 \text{ KW/m}^2\) at \(349.8^\circ\text{C}\), \(26.06 \text{ KW/m}^2\) at \(519^\circ\text{C}\), \(17.11 \text{ KW/m}^2\) at \(478.5^\circ\text{C}\), \(16.79 \text{ KW/m}^2\) at \(469.2^\circ\text{C}\) for water, vegetable oil, lubricating 2T oil, and lubricating 4T oil. Among these, the maximum heat flux occurs when stainless steel probe is quenched in vegetable oil during quenching.

![Figure 3](image3.png)

**Figure 3** Cooling Rate for different quenchants.

![Figure 4](image4.png)

**Figure 4** Heat flux variation for different quenchants.
5. Conclusions
Experiments are conducted to analyse cooling rate and heat flux during quenching of stainless steel specimen with various quenchants. Using this data with coupled inverse heat transfer solver is used to determine heat flux and surface cooling rates. The results show that the cooling curves depending on the quenchants. The cooling curves are cross over each other. This indicates that there is an identical heat transfer to be takes place. The magnitude of heat flux also varies significantly for different quenchants. The maximum cooling rates for the specimen 170°C/s, 75°C/s, 59°C/s, 55°C/s, at a temperature of 425°C, 655°C, 582°C, 496°C for distilled water, vegetable oil, lubricating oil 4T and 2T oil respectively. At higher temperature there is a film boiling takes place. Due to this the heat flux is to be minimum. The convective heat transfer coefficient is low because the energy absorbed by the quenchants is slow. In nucleate boiling region there is increase in heat flux and convective heat transfer coefficient is increased due to decrease in temperature. Cooling rate decreases at the lower temperature the heat flux is variation of stainless steel materials decreased. The transfer through natural convection only.

Present work is able to analyse complicated boiling heat transfer phenomena for transient heat treatment process.

References
[1] Prasanna Kumar T. S, Hernandez-Morales B., and Totten, G. E., 2014, Reference QuenchProbe”—An Alternative Probe Design for In-Situ Estimation of Cooling Rates, Heat Flux, and Hardenability During Immersion Quenching of Hardenable Steels, Materials Performance and Characterization January (2015)
[2] Elmi Hosseini, S. R., Zabet, A., and Li, Zhuguo 2014, Cooling Curve Analysis Of Heat Treating Oils And Correlation With Harden And Micro-structure Of Low Carbon Steel 2014, Materials Performance and Characterization, Vol. 3, No. 4, 2014, pp. 427–445.
[3] T.S. Prasanna Kumar, 2013, Influence of Steel Grade on Surface Cooling Rates and Heat Flux during Quenching, Journal of Materials Engineering and Performance. ASM International JMPEG (2013) 22:1848-1854
[4] G. Ramesh and K. Narayan Prabhu, 2014, Effect of thermal conductivity and viscosity on cooling performance of liquid quench media, International Heat Treatment and Surface Engineering, 8:1, 24-28.
[5] Ester Carvalhode Souza, Lauralice C.F. Canale, G.Sanchez Sarmiento, Eliana Agaliotis, Juan C. Carrara, Diego S. Schicchi, and George E. Totten, 2013, Heat Transfer Properties of a Series of Oxidized and Unoxidized Vegetable Oils in Comparison with Petroleum Oil-Based Quenchants, Journal of Materials Engineering and Performance Volume 22(7) July 2013—1871.
[6] J. K. Odusote, T. K. Ajiboye and A. B. Rabiu, 2015, Effect of Vegetable oil Quenchants On The Properties Of Aluminium During Solution Heat Treatment. Journal of Mechanical Engineering and Sciences (JMES); Volume 8, pp. 1343-1350, June 2015 ISSN (Print): 2289-4659; e-ISSN: 2231-8380..
[7] AtulShelar, Kiran Wale, Manoj Muchalambe and SurajPattekar, 2019, Study of Mechanism of Quenching & Calculate the Cooling Rate of Quenching Oils by Quenching Instrument. International Research Journal of Engineering and Technology (IRJET) volume 05 May (2015) -ISSN: 2395-0056.

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