COMPARATIVE ANALYSIS OF HEAT TRANSFER CHARACTERISTICS DURING QUENCHING OF EN 9 STEEL: CFD AND EXPERIMENTAL

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Abstract—Heat treatment is the process used for the alteration of physical properties of the material under treatment for their suitability of structural and functional requirement. The thermal simulation of the heat treating process is usually a transient type of temperature analysis, in which the hot metal part temperature changes with respect to time from an initial state to a final state. In the simulation, initial temperature of the hot part and temperature of quenchant are usually easy to obtain and can be assigned with reasonably accurate values. So are the thermo physical properties of the part material. The critical part is to determine the heat transfer coefficient between the hot part and quenchant. In liquid quenching, the heat transfer between hot metal parts and water is very complicated and it is difficult to determine the HTC. For this experimentation the EN 9 steel rod with Φ50 mm and length 100 mm along with water and ethylene glycol mixture with different concentrations as quenching medium are used. More and more attention is paid to numerical modelling using finite element packages and computational fluid dynamic packages for the benefits on money and time saving. A part model is created in 3-D form, then the model is meshed and by applying the actual boundary conditions the CFD analysis is conducted. In order to validate CFD analysis the experimental trials are conducted. In this paper the conducted experimental trials are discussed and compared with the CFD results.

Keywords—Quenching, HTC, CFD, heat flux, cracking, and temperature gradient.

I. INTRODUCTION

In order to prevent the harmful effects of distortion, residual stress and cracking while improve the mechanical properties of steel alloy components, it is highly necessary for heat treaters to optimize component designs and heat treating processes. Experimental trials are used to determine better component designs and process setups, but more and more attentions are being paid to numerical modelling using finite element packages and computational fluid dynamic packages for the benefits on money and time saving. Numerical simulations of quenching of metal parts are usually carried out by finite element analysis packages such as ABAQUS, ANSYS, etc., a CAD model of the part needs to create in 2-D or 3-D form, then the model can be meshed with suitable elements. For quenching simulations, the temperature-displacement simulation is usually decoupled to thermal simulation and structure simulation in industrial practice for two reasons. First, decoupled simulation scheme requires less memory and converges faster than the coupled one. Second, the results from these two schemes are similar since in heat treating processes the heat generated by deformation is usually negligible compared to the heat transferred from hot solid to environmental media. Thus, thermal simulation needs to be first carry out to obtain temperature-time profile of the part. The followed structural simulation reads the temperature time profile and predicts quenching results such as distortion and residual stresses. In order to obtain high accurate simulation results, the finite element modelling must be validated by experimental measurements of residual stresses, distortion, etc. The thermal simulation of a heat treating process is usually a transient temperature analysis, in which the hot part temperature changes with respect to time from an initial state to a final state. In the simulation, initial temperature of the hot part and temperature of quenchant are usually easy to obtain and can be assigned with reasonably accurate values. So are the thermo physical properties of the part material. The biggest uncertainty is the heat transfer coefficient (HTC) between the hot part and quenchant. It has been reported that HTC affects the quenching result significantly.
In liquid quenching, the heat transfer between hot metal parts and water is very complicated and it is difficult to determine the HTC. When a hot part is quenched in a fluid like oil or water, there are usually 3 stages: vapour stage, boiling stage and convection stage. The complicated interactions between solid and fluid lead to very complicated HTC data, which are not uniform in both time and space. Because of the importance of HTC and the determination difficulty, efforts must be made to acquire HTC distribution for a specific part as real as possible. Classical empirical equations from heat transfer textbooks are usually not suitable for real parts because of the complicated interaction and geometry. Current CFD packages are also facing difficulties on this issue. In the structural simulation, the temperature-time profile from the thermal simulation is read in and the part is shrunk due to the temperature drop. The non-uniform thermal shrinkage is constrained by the geometric structure and material strength that is varying with respect to temperature, strain, strain rate, etc. In other words, some portions of the part may not be able to move freely and therefore experience yielding. Thus, how the material behavior during quenching is governed is extremely important to the simulation accuracy. Quenching results such as temperature-time profile, residual stress and distortion can be predicted by numerical simulations and can be evaluated by experimental measurements. Temperature-time curves acquired from experiments can be used to evaluate the accuracy of thermal model, especially boundary conditions like HTC data. Comparison between predicted distortion and measured one is a good choice to evaluate the accuracy of finite element models, especially the material models in the structural analysis.

II. LITERATURE REVIEW

N. Lior [2] studied the cooling process in gas quenching. To that end, the authors researched the state of the art, and have conducted numerous numerical and experimental studies and developed CFD models on this subject, and show the results for flows inside quench chambers and their components, and for external flows, including multi-jet impingement, on cylindrical and prismatic single and multiple bodies (the quench charge). This can be most effectively done by preliminary CFD modelling and simulation. Li Huiping et al [7] during their study of the evaluation of surface heat transfer coefficients by using experiment measurement method came to know that as per the characteristics of quenching process it was necessary to have high speed data acquisition system. The rate of decrease in temperature was too high. For recording the temperature drop so that the accuracy of the temperature measurement and to study the characteristics of quenching process, a high-speed data acquisition system for measuring The temperature variations in a quenched part is needs to be set up by using industry standard architecture (ISA) which is discussed in this paper. Osman and Beck et al [9] used Beck’s method for estimation of the transient heat transfer coefficient history from interior transient temperature measurements during quenching of copper sphere into cooling baths without boiling. They treated this problem as a nonlinear parameter estimation problem. The unknown heat transfer coefficient was assumed to be a piece wise constant function of time and was estimated using the sequential function specification method. Liscic et al [10] proposed a temperature gradient method to estimate heat flux during quenching. They used a specially designed quench probe for the determination of temperature gradient on the surface. Diller and Onishi patented a method for measurement of surface heat transfer by heat flux gage applied to a surface. However, the above methods require the use of specially designed sensors. Most of the quenching heat transfer research work involves the estimation of surface heat transfer coefficients/heat flux transients by measurement of the thermal history inside the quench probe during quenching. The measured temperature data and thermo-physical properties of the metal are used to solve the heat conduction equation inversely to determine the surface heat flux and temperature. Kim and Oh et al [11] have shown spatial distribution of heat transfer coefficient during fan cooling and water quenching of carbon steel specimen heated to 500 °C. However, the research work was mainly focused on the development of IHCP algorithm for estimation of multiple heat transfer coefficient/heat flux transients during quenching. The importance of estimating the spatial dependent heat flux transients was not highlighted. Heat transfer during quenching of gear blank in agitated and stagnant oil. They
used whole domain-optimizer technique, which is coupled to a direct solver of the heat conduction equation to set up and solve the inverse problem to calculate heat flux transients at different locations of gear blank. Peter Fernandes [13] et al made an attempt to determine the heat flux transients during quenching of Ø28 mm×56 mm height and Ø44 mm×88 mm height AISI 1040 steel specimens during lateral quenching in brine, water, palm oil and mineral oil and the heat flux transients are estimated by inverse modelling of heat conduction. The variation of heat flux transients with surface temperature for different quenching media was investigated in different experiments. Higher peak heat flux transients are obtained for 28mm diameter specimen than 44mm diameter specimen during quenching in aqueous medium. The study leads to the final conclusion that agitation of quenching medium increases the peak heat flux during the quenching of steel specimen in all the quenching mediums. Peak hardness is obtained at the surface and with smaller diameter specimens during Agitation.

III. EXPERIMENTAL WORK

3.1 Assumptions
The medium carbon steel specimen taken for the experimental work as well as quenching medium are considered homogeneous. Properties of quenching medium changes with respect to temperature. Changes in Latent heat during phase change solid – solid of specimen material is neglected. Domain boundaries are considered to be continuously expanding and hence heating of medium due to boundary is neglected. Initially fluid is considered at rest i.e. no convection at start of experimental trial. No agitation is provided to specimen. Temperature at start of trial is uniform for quenching medium as well as for solid specimen. The figure 3.1 shows the experimental set up for quenching process.

3.2 Material composition
The specimen model is cylindrical roller with diameter 0.05m and length 0.1m.

<table>
<thead>
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<th>Constituent</th>
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<td>3</td>
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<tr>
<td>4</td>
<td>Sulphur</td>
<td>0.05 %</td>
</tr>
<tr>
<td>5</td>
<td>Iron</td>
<td>Remaining</td>
</tr>
</tbody>
</table>

3.3 Specimen boundary conditions:
At t =0 sec \( T_s = 1173 \) K
Quenching medium initial temperature: 298K
Fluid tank size: 30cm X 30cm X 20cm
Fluid domain Boundary Condition: \( T_m = 298K \), \( P = 1.013 \) bar

3.4 Heat Treatment
The cylindrical specimen with diameter 0.05m and length 0.1m are made from EN 9 steel rod. The K type thermocouples are brazed at the center, top and curved surface of the specimen as shown in set up diagram. The thermocouple are connected to the temperature indicator for the
temperature measurement. This thermocouple connected assembly is placed in the furnace for heating up to austenitising temperature range of steel. Specimen is heated in muffle furnace up to 900°C for 15-20 minutes and then transferred in the quenching tank containing quenchant i.e. water, 20%, 40% and 60% of EG in water by mass. The heating range and soaking times for the experimental investigations were selected based on the material composition of the specimens.

IV. RESULTS AND DISCUSSION

The heat treatment of EN9 steel is conducted and the measured temperature variation against the time is plotted. More trials are conducted to ensure the repeatability of the quenching process. Here are the plots of different trials taken for the different concentrations of ethylene glycol in water.

4.1 CFD Analysis

The specimen can be modelled by using different CAD software which is compatible with the computational fluid dynamics software. For the current modelling, Pro-ENGINEER WILDFIRE 5.0 has been used. The models so formed are along with the fluid domain where in the effects of the heat flow has to be analyzed.

![Figure 4.1 3D Model of Solid Specimen](image1)

![Figure 4.2 Meshing of Outer Domain](image2)

![Figure 4.3 Top View of Solid Domain](image3)

The above solid domain model shows the meshing using hexahedron elements and structured type of mesh. Above model also shows that meshing of fluid domain near solid domain is finer due to requirement of more accuracy and mesh size goes on increasing as we move away from solid domain. The thermal performance is analyzed for work piece to be quenched. Different trials are taken by varying quenching medium with increasing concentration of ethylene glycol by mass. The results obtained are discussed here.

4.1.1 Temperature vs. Time

The software analysis of the quenching process includes the temperature versus time plot of the surface and top surface. The graph shown below shows the variation of cooling at curved surface and center of the specimen.
The above graph [Figure 4.4] shows variation of temperature with respect to time for surface and core. The cooling rate is higher as compared to the cooling rate for the core of the specimen. We can observe large temperature difference between surface and core of the specimen because the core cools by conduction while surface cools by convection. Due to variation in cooling of surface and core there will be uneven contraction of material of specimen which is responsible for residual stresses. The above graph [Figure 4.5] shows variation of temperature with respect to time for surface and core when quenching medium is 20% ethylene glycol solution by volume. The temperature variation between surface and specimen at particular instant is less compare to previous quenching medium which leads to less residual stress formation compare to previous trial.

The above graph [Figure 4.6] shows variation of temperature with respect to time for surface and core when quenching medium is 40% ethylene glycol solution by mass. The cooling rate is slowest for this trial. As percentage of ethylene glycol increases in aqueous solution rate of heat transfer from surface to quenching medium decreases. Heat transfer by convection approaches the heat transfer by conduction within specimen and hence temperature gradient between surface and core of specimen is least for this trial. We can predict that residual stress formation is least for this trial. As percentage of ethylene glycol increases in quenching medium the temperature gradient goes on decreases and it will result in less residual stress formation. We can also ensure the formation of martensite throughout the work piece by comparing slowest cooling curve with critical cooling curve. The above graph [Figure 4.7] shows variation of temperature with respect to time for surface and core when quenching medium is 60% ethylene glycol solution by mass. The cooling rate is slowest for this trial. As percentage of ethylene glycol increases in aqueous solution rate of heat transfer from surface to quenching medium decreases. Heat transfer by convection approaches the heat transfer by conduction within specimen and hence temperature gradient between surface and core of specimen is least for this trial. We can predict that residual stress formation is least for this trial. As percentage of ethylene glycol increases in quenching medium the temperature gradient goes on decreases and it will result in less residual stress formation. We can also ensure the formation of martensite throughout the work piece by comparing slowest cooling curve with critical cooling curve.
4.1.2 HTC vs Time

The figure 4.8 shown below is the variation of heat transfer coefficient during the quenching process of EN steel specimen, when quenching medium is water. It shows that HTC at the circumference of specimen is more as compared to that at top.

![Figure 4.8 HTC vs. Time (0% EG)](image1)

![Figure 4.9 HTC vs. Time (20% EG)](image2)

The plot of HTC versus time for the 20% ethylene glycol concentration by volume in water (Figure 4.9) shows the reduction in HTC at circumference as well as at the top of surface. The reduced values of HTC indicates the reduced rate of convection at metal quenchant boundary of heated specimen and mixture of Ethylene glycol in water. The figure 4.10 shows the plot of heat transfer coefficient against time. The HTC at circumference is reducing with the addition of ethylene glycol. If this graph is compared with previous graphs it shows the similar nature with reduced values of heat transfer coefficient at all the times.

![Figure 4.10 HTC vs. Time (40% EG)](image3)

![Figure 4.11 HTC vs. Time (60% EG)](image4)

Figure 4.11 is the graph of heat transfer coefficient on curved and top surface of the steel specimen quenched in 60% concentration of ethylene glycol in water by volume. If this graph is compared with earlier graphs for 0%, 20% and 40% EG concentration, it shows HTC values for curved and top surface are lower for the increasing concentration of EG, which indicates the reduction in the convective heat transfer.

4.3 Comparison of CFD and Experimental results

4.3.1 Comparison of CFD and Experimental cooling rate

The graph (Figure 4.12) is the comparative plot for the temperature versus time for 0% EG. It shows that initially the rate of cooling is greater for the actual measurement for the temperature then after it reduces. (Here C-Center while S-Surface of specimen)
For water as a quenching medium it shows variation of cooling between core and surface, with large temperature gradient. Such conditions are not feasible for the components with larger sections. It may leads to the structural and functional failure. The graph (Figure 4.13) represents the temperature versus time variation for 20% EG concentration in water by volume. The actual cooling rate for the surface and core of the specimen is closely resembles the cooling rate obtained by CFD. It shows the cooling rate is reduced due to addition of EG. It results in reduction of temperature variation between core and surface, which is desirable for reducing the distortion tendency.

The graph (Figure 4.14) represents the temperature versus time variation for 40% concentration of EG by volume. If this graph is compared with the other concentrations, it shows the rate of cooling of the surface is greatly reducing with addition of EG.

The figure 4.15 is the indication of slowest cooling rate that is obtained for 60% concentration of EG by volume in the water. The graph shows the visible difference of reduced temperature variation between core and surface. Also towards the end of quenching process the cooling rate is observed more for the actual measurements as compared to rate of cooling obtained in CFD. From all the graphs of cooling curves that are obtained from experimental results and CFD, we can say that addition of ethylene glycol reduces the cooling rate of specimen. This reduction is observed due to reduction in heat carrying capacity of the mixture. It reduces the rate of convective heat transfer. Also the cooling curves obtained by both experimental and from CFD are closely resembles, except towards the end of quenching. It is observed that at the end of quenching, in all the cases cooling rate was lower for the actual measurements.

4.3.2 Comparison of CFD and Experimental HTC

The graph (Figure 4.16) shown is the comparison between CFD and experimental heat transfer coefficient obtained at the curved surface. It is observed that HTC for the results obtained
from experimental values is lower as compared to that by CFD. The graph clearly indicates that the variation of HTC obtained by the CFD is higher at all the times if it is compared with actual HTC distribution, for the curved as well as the top of the specimen.

The graph (Figure 4.17) is the plot of HTC vs Time for the 20% EG concentration. The experimental and CFD results shows that HTC values are decreased for the addition of ethylene glycol. Also HTC obtained by CFD is higher as compared to that for the experimental results. The reduced values indicate that the heat carrying capacity of the mixture is reduced. Also reductions in the experimental values of heat transfer coefficient are due to cooling effect during transfer of heated specimen from furnace to the tank. It results in reduced temperature gradients which results in lower HTC values.

The graph (Figure 4.18) shown is the comparative plot of HTC vs Time for the 40% EG concentration for both curved and top surface of specimen. The above plot for the 60% EG concentration (Figure 4.19) shown above. If it is compared with the previous graphs it shows the same nature. HTC obtained by CFD is higher as compared to that for the experimental results. The reduced values indicate that the heat carrying capacity of the mixture is reduced. Also reductions in the experimental values of heat transfer coefficient are due to cooling effect during transfer of heated specimen from furnace to the tank. It results in reduced temperature gradients which results in lower HTC values.

V. CONCLUSION

Based on the measurements during the experimentation the data obtained is used to plot the graphs. The experimental data when compared with CFD analysis, it leads to the following conclusions,
1) Quenching analysis by CFD for temperature versus time plot shows the reduction in cooling rate of the specimen with increase in concentration of ethylene glycol.

2) The reduced cooling rate results in reduction of temperature difference between surface and core of the specimen.

3) CFD results of Heat transfer coefficient at the curved surface are more as compared to HTC on top and bottom of the specimen at all the times.

4) Experimental results shows the reduced cooling rate of the specimen, which indicates the reduction in heat carrying capacity of the mixture with addition of ethylene glycol.

5) The value determined from experimental results for heat transfer coefficient is found to be more for the curved surface of the specimen as compared to that for the top of the specimen.

6) Initially the value of HTC is lower and it increases suddenly, which is the indication of occurrence of nucleate boiling, and then after HTC decreases for both curved as well as top of specimen.

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REFERENCES


