DETERMINATION OF SURFACE HEAT TRANSFER COEFFICIENT DURING QUENCHING OF MEDIUM CARBON STEEL

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Abstract- Quenching is an important heat treatment processes during manufacturing of mechanical component. The purpose of quenching is intentional introduction of desired mechanical properties in the components, which will improve their structural as well as functional appearance. Heat treatment is generally followed by transfer of heated component to the environment which uses the quenchants such as forced gas, oil or water flow. During the quenching process, heat is transferred from hot metal component to the quenching medium. This heat transfer in quenching process results in faster cooling of surface than core of the component. This variation in cooling rates may give introduce residual stress and cause distortion and cracking. This variation is due to difference in conduction and convection heat transfer rates. It needs to optimize the quenching process for both part geometry and quenching process design to minimize such problems while improving mechanical properties. In this work the attempt is made to conduct experimental trial of quenching of medium carbon steel with the intention of determination of surface heat transfer coefficient of cylindrical component of material EN 9 steel. The temperature variation during the quenching process is recorded by using K type thermocouple and temperature indicator. Data obtained by experimental work is used to plot temperature variation to observe the variation of cooling rate. From the obtained data HTC is calculated and plotted against time.

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

I. INTRODUCTION

Heat is transfer either by conduction, convection or radiation. The quenching process can be realized by considering the modes of heat transfer that take place during conventional quenching. Boiling of the quenchant on the heated part surface starts immediately when the part is immersed into the quenching tank. The high heat flux from the part surface results in very high rate of water Evaporation that a vapor blanket (a vapor film) covers all or part of the heated surface. This mode of heat transfer is called film boiling. The film boiling is a non-controllable process because the vapour blanket appears and disappears throughout the part surface. Film boiling is the least uniform phase during quenching causing the most part distortion. During film boiling stage of cooling a heat flux from the part surface decreases since the vapour blanket acts as an insulator and results in a high thermal resistance for moving the heat from the heated component to the quenchant. The decrease in the heat flow rate from the heated component surface results in the reduction of the quenchant evaporation rate. As the time goes, the vapour blanket collapses and the film-boiling mode of heat transfer disappears and this leads to the nucleate boiling stage. During the nucleate boiling mode of heat transfer, small bubbles are formed at the surface. As the time goes there is no more vapour formation around the heated part surface, and then the heat flow rate decreases, due to the reduction of the temperature gradient. The heat transfer throughout the nucleate boiling stage of cooling is the highest value of heat flow rate during the quenching process. After nucleate boiling , further heat transfer takes place by convection. Convection heat transfer is the slowest (least intensive) mode of the heat extraction during the conventional quenching processes.

II. LITERATURE REVIEW

Quench hardening of steel involves three steps: (i) heating of components to austenitising temperature usually in the range of 850 ^{0}C – 870 ^{0}C, (ii) holding it at that temperature for a particular of time and (iii) quenching (rapid cooling) in a suitable quench medium to room temperature

[1].Quenching is the critical step which involves simultaneous occurrence of different physical events such as heat transfer, phase transformation and stress/strain evolution. Heat transfer is the driving physical event as it triggers other processes. M Eshraghi Kakhki et al [1] conducted experiment and modelling for the application of polymeric quenchant in heat treatment of crack sensitive steel and stated that success or failure of quenching process is decided by the selection of appropriate quenchant. In this paper the quenching process of automobile tie rods in different media including water, oil and polymeric solution was investigated. The microstructure and the mechanical properties were predicted by finite element simulation model. Several specimen were cut from the tie rod and quenched in different cooling media. The hardness test and metallographic test were performed. The experimental outcomes shows that the application of polymeric quenchant outperforms the water and oil quenchant. The distortion and cracking was reduced as compared to water and oils which was observed due to variation in cooling rates at the surface and core of the specimen. N. Lior [2] studied the cooling process in gas quenching a relatively new process with several important advantages, such as minimum environmental impact, clean products, and ability to control the cooling locally and temporally for best product properties. In order to meet the high cooling rates required for quenching, the cooling gas must flow at very high velocities, and such flows are highly turbulent and separated. A. Buczek et al [3] during the study of heat transfer coefficient during quenching in various cooling agents authors Measured and evaluated the value of Heat transfer coefficients (HTCs) at the surface of a metal sample during immersion quenching, using numerical procedures. A FEM self-developed computer code is used to obtain a solution to the direct problem. The sensitivity of the method enabled them to examine the effect of various quenching parameters on the heat transfer for two mineral oils and a polymer quenchant. T Telejko et al [4] studied the inverse determination of the boundary conditions during boiling water heat transfer in quenching operation. From the results it is clear that, while cooling in the mineral water, the value of heat transfer coefficient increases with an increase of quenchant temperature, particularly near the peak of HTC versus surface temperature curve. The cooling rates were different at surface and core. The surface cools faster as compared to core, which leads to distortion. Frank Puschmann et al [5] studied the Transient measurement of heat transfer in metal quenching with atomized sprays. In atomized spray quenching water is atomized with the help of compressed air. The drop flow produced is sprayed onto a hot surface. The drops partially evaporate there and are carried away by air flow afterwards. An irregular collapse of steam film at corners, edges and surface roughness, as known from water spray quenching, does not occur. The influence of water impingement density, distribution of drop diameter, distribution of drop velocity, surface temperature and air flow superposed are investigated with the help of a transient measurement procedure. Li Huiping et al [6] during the study of quenching process for determination of heat transfer coefficient, had conducted the experiments and the inverse heat conduction approach is used for determination of HTC. The authors introduces a new method to calculate the temperature dependent surface heat transfer coefficient during quenching process and calculated the surface heat transfer coefficient according to the temperature curve gained by experiment. They stated that during the calculation process, the phase-transformation volume and phase-transformation latent heat of every element in every time interval can be calculated easily by FEM. K. Narayan Prabhu et al [8] had studied the axial and radial heat transfer during immersion quenching of Inconel 600 probe. During their work the authors conducted the immersion quenching of Inconel 600 probe in mineral oil quench medium and the time–temperature data obtained at axial and radial locations were measured during the process. The cooling of probe was not uniform during quenching process. The variation of cooling rate along the axial direction was found to be higher as compared to the radial direction. Inverse heat conduction problem (IHCP) was solved for the estimation of heat flux transients. For the calculation of heat flux, Single and multiple unknown heat fluxes were assigned on the metal/quenchant boundary and it was found that the error between the estimated and measured temperature is reduced significantly with increase in number of unknown surface heat flux components.

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.
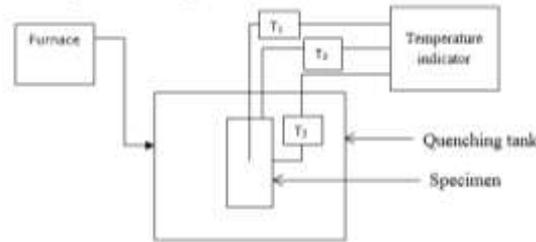
Figure 3.1 Experimental set up

3.2 Material composition

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

Table 1: Material composition of EN 09 steel

No	Constituent	% content
1	Carbon	0.55 %
2	Manganese	09 %
3	Phosphorous	0.04%
4	Sulphur	0.05%
5	Iron	Remaining

3.3 Specimen boundary conditions:

At t =0 sec   Ts = 1173 K   Quenching medium initial temperature: 298K
Fluid tank size: 30cm X 30cm X 20cm
Fluid domain Boundary Condition: Tm= 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 Repeatability check

Here is the graph of temperature vs. Time plotted for the two trials conducted for the 20% concentration of Ethylene glycol in water.
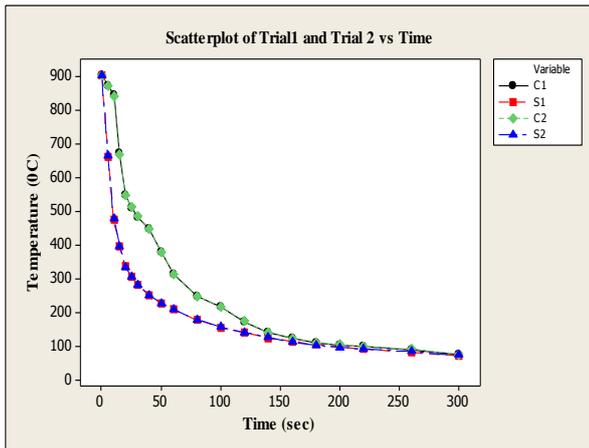
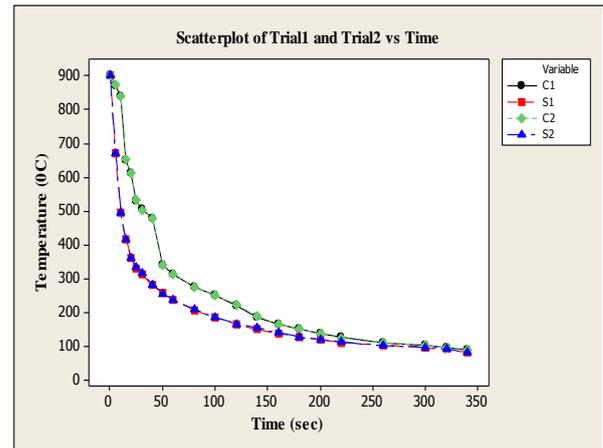

Figure 4.1 Temperature vs. Time Plot for 20 % EG

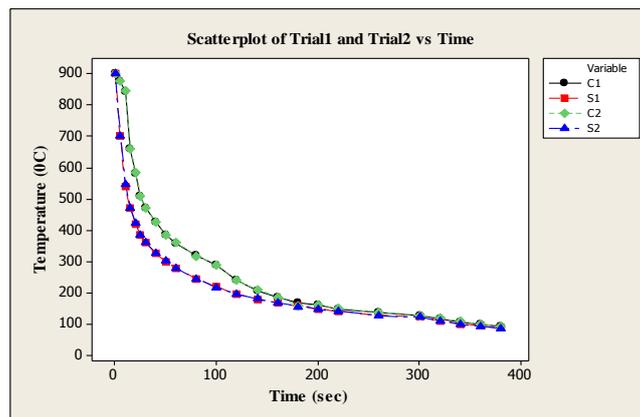*Figure 4.2 Temperature vs. Time Plot for 40 % EG*

Figure 4.3 Temperature vs. Time Plot for 60 % EG

The above graph [Figure 4.1] shows the quenching process of EN9 steel at the 20 % concentration of ethylene glycol is reproducible. Both the trials shows the repeatability of the temperature distribution during quenching. The temperature difference is very less so that it can be neglected. The quenching is conducted twice to ensure the reproducibility of the process. The graph shows [Figure 4.2] the plot of temperature vs. Time plotted for the two trials conducted for the 40% concentration of Ethylene glycol in water and graph [Figure 4.3] is the plot of temperature vs. time for 60 % concentration of Ethylene glycol in water. The above graphs [Figure 4.2] and [Figure 4.3] shows the quenching process of EN9 steel at the 40 % and 60 % concentration of ethylene glycol are with very less or negligible variation and quenching is reproducible. Two trials are conducted for both the concentrations and the trials shows the repeatability of the temperature distribution during quenching. The temperature difference is very less so that it can be neglected.

4.2 Temperature vs. Time

The experimental trials were conducted for the quenching of EN9 steel in aqueous solution of ethylene glycol in water and the temperature distribution during the process is plotted against time to observe the cooling rate variation with addition of Ethylene glycol with different concentrations.
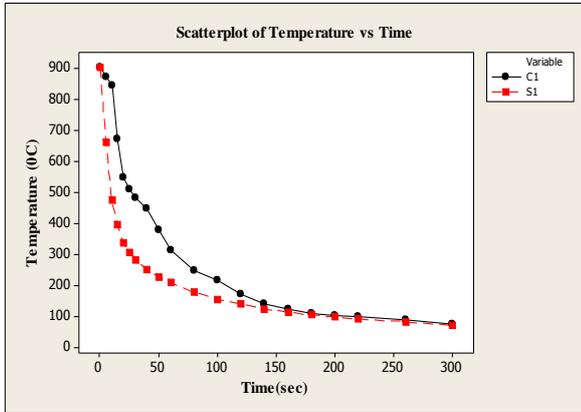
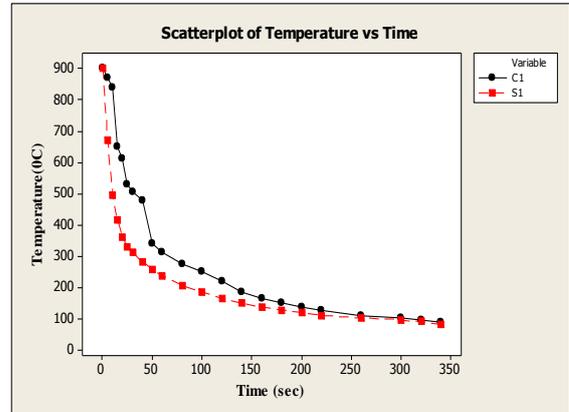*Figure 4.4 Temperature vs Time Plot for 0 % EG*

Figure 4.5 Temperature vs Time Plot for 20 % EG

The above graph [Figure 4.4] shows the quenching process of EN9 steel in water. The temperature variation with respect to time for surface and core are plotted in the above graph. We can observe large temperature difference between surface and core of the specimen. This variation is due to variation in the cooling rate of surface and core of the specimen. This variation in cooling of surface and core may leads to uneven contraction of material when it is subjected to sudden cooling of specimen which is responsible for distortion and cracking along with residual stresses. Ethylene glycol is the polymer which is having lower specific heat capacity as compared to water is added to water, with 20% by volume. The heated specimen is then transferred from furnace to quenching tank and the temperature variation during the process is measured. The graph [Figure 4.5] shows the temperature distribution with time, on curved surface and center of the steel specimen. If the above graph is compared with the graph for water as a quenchant then we can say that the temperature variation between surface and core of the specimen at particular instant is less in graph [Figure 4.5] compare to the same in graph [Figure 4.4] which leads to less residual stress formation compare to previous trial.
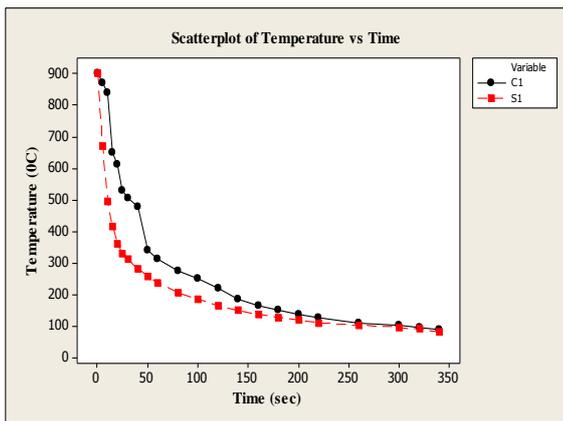

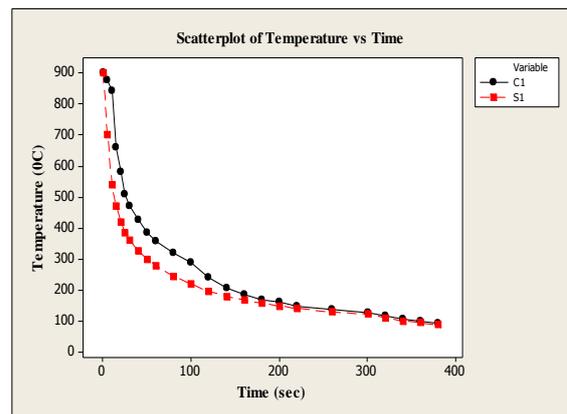*Figure 4.6 Temperature vs Time Plot for 40 % EG*

Figure 4.7 Temperature vs Time Plot for 60 % EG

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 in solution by volume. The cooling rate is slower for this trial. If this graph is compared with earlier graphs, it shows the visible difference of temperature variation between core and surface. The convective heat transfer rate is reducing with addition of ethylene glycol. The difference between core and surface temperature at a particular time instant is reduced. The figure 4.7 is the plot for the 60 % of EG in water. It shows variation of temperature with respect to time for surface and core when quenching medium is 60% ethylene glycol solution by volume. 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.

4.3 HTC vs TIME

From the data of temperature distribution and cooling rate obtained from the graphs for different concentrations heat transfer coefficients at during different time intervals are calculated for the vertical curved surface and top surface of the steel specimen. The values obtained from the calculations are then used to plot the HTC variation during quenching.
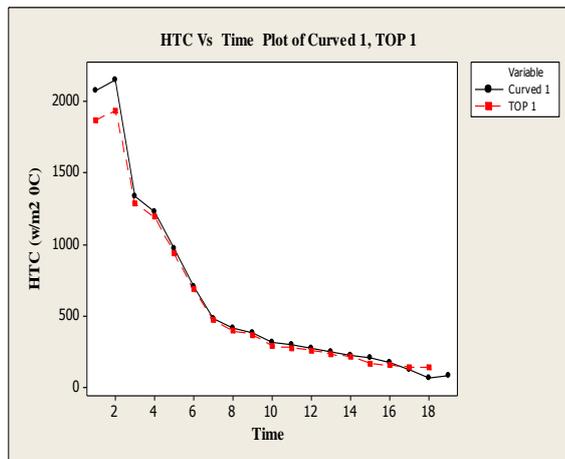

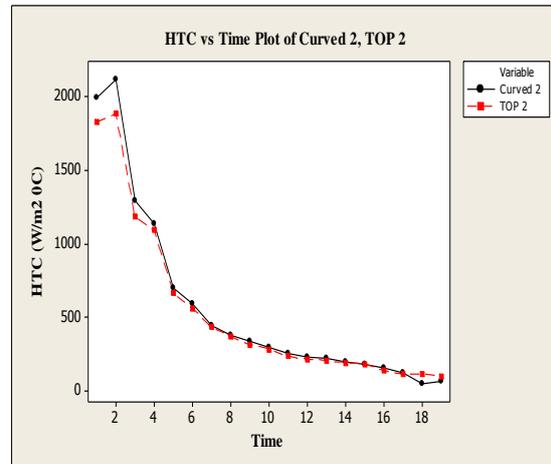*Figure 4.8 HTC vs. Time Plot For 0 % EG*   *Figure 4.9 HTC vs. Time Plot For 20 % EG*

Above graph [Figure 4.8] shows the variation of HTC with respect to time when quenching medium contains 0% concentration of ethylene glycol by volume. It shows that HTC is more for curved surface of the cylindrical specimen and it is significantly less for top during the process of quenching initially there is evaporation of water and it forms vapour blanket around the specimen which acts as insulation and the heat transfer is less. As time goes it appears nucleate boiling and here heat transfer rate is very high and hence it approaches the maximum value. After some time natural convection starts where HTC is lower and it goes on reducing. Heat transfer coefficient has the maximum value of 2147.18 W/m^2 ^{0}C and that for the top of the specimen is 1934.41 W/m^2 ^{0}C. The graph [Figure 4.9] shows the variation of HTC with respect to time when quenching medium contains 20% concentration of ethylene glycol by volume. The graph shows similar nature as that of the previous condition. Here also we can observe that HTC at curved surface is more as compared to HTC at the top of the specimen. But due to addition of 20% ethylene glycol solution HTC decrease and it approaches maximum value 2113.37 W/m^{2}k.The reason of getting higher value on the curved surface is the way to easy escape of the bubbles formed during nucleate boiling, which carries more heat. As the time passes the heat transfer coefficient values are getting closer for both the cases.
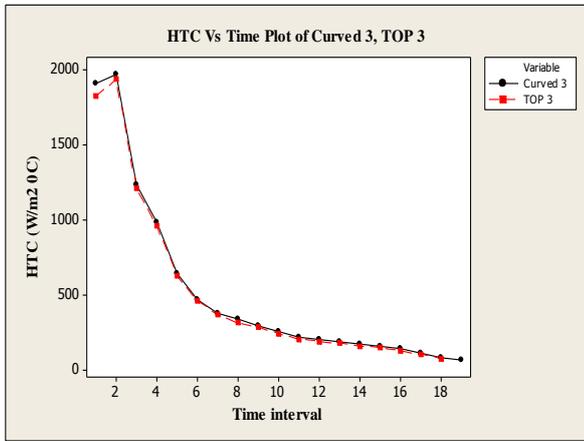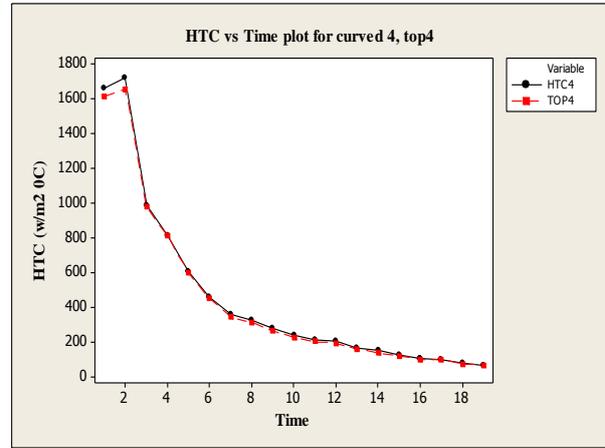
Figure 4.10 HTC vs. Time Plot For 40 % EG

4.11 HTC vs. Time Plot For 60 % EG

Above graph [Figure 4.10] shows the variation of HTC with respect to time when quenching medium contains 40% concentration of ethylene glycol in water by volume. The graph shows similar nature as that of the previous condition. But due to addition of 40% ethylene glycol solution the rate of convective heat transfer decreases which results in decrease of HTC and it approaches maximum value 1968.14 W/m^2 ^{0}C and that on 1938.15 W/m^2 ^{0}C. We can say that addition of ethylene glycol reduces the HTC during quenching process and ultimately reduces the cooling rate of the specimen. Initially the value of heat transfer coefficient is lower and it increases suddenly. The sudden rise in HTC indicates the nucleate boiling stage during which heat transfer rate increases. As the time goes the convection heat transfer starts and HTC goes on decreasing.

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. In this case the maximum value of heat transfer coefficient is 1741.47 W/m^2 ^{0}C for curved surface of the specimen.
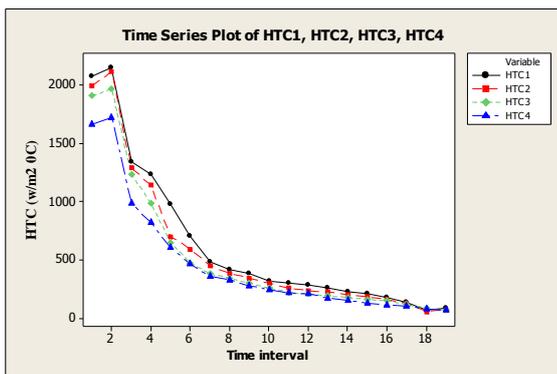

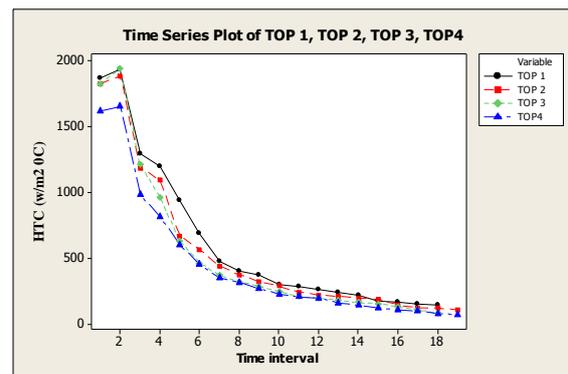*Figure 4.12 HTC vs Time at curved surface*

Figure 4.13 HTC vs Time at curved surface

In Figure 4.12, the heat transfer coefficient on curved surface is plotted against time. It is simultaneous plot of for all concentrations, which shows as the concentration of ethylene glycol increases the heat carrying capacity of the mixture reduces. The reduction can be predicted by the nature of the cooling curves of steel specimen for all the concentrations. This reduction in the heat carrying capacity reduces the rate of convective heat transfer from the metal quenchant interface, which is indicated by the HTC plot of all concentrations [Figure 4.12]. Figure 4.13 is the plot of heat transfer coefficient at the top of the specimen versus time. It shows four curves for 0%, 20%, 40% and 60% concentration of ethylene glycol in water by volume. The above graph indicates that HTC decreases with increase in EG concentration. Also heat transfer coefficient at the top surface is always lower than that at curved surface.

V. CONCLUSION

The experimental work of quenching of medium carbon steel is conducted and temperature variation is recorded. The data obtained is used for the estimation of heat transfer coefficient. The values of HTC calculated at the curved surface and top surface of the specimen. The experiment leads to the following conclusion,

1) There is variation in cooling rate at the surface and core of the cylindrical specimen.
2) Increase in the concentration of ethylene glycol reduces the temperature difference between core and surface of specimen, during quenching.
3) Addition of EG reduces the rate of convective heat transfer from the surface, which reduces temperature variation between surface and core during quenching.
4) Reduction in variation of temperature between surface and core ensures less possibility of distortion and cracking.
5) The cooling rate is observed more on the curved surface as compared to that at the top of the specimen.
6) Due to addition of ethylene glycol Heat transfer coefficient decreases.

VI. ACKNOWLEDGEMENTS

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