Study of Heat Transfer Characteristics of Medium Carbon Steel During Polymer Quenching

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Abstract: After heat treatment Steel components are generally quenched in forced gas, oil or water flow to improve mechanical properties and improve product life. During the quenching process, heat is transferred rapidly from the hot metal component to the surrounding medium and the rapid temperature drop which causes phase transformation and deformation in the hot metal component. This rapid heat transfer in quenching process gives rise distortion, cracking and high residual stresses. To minimize such problems while improving mechanical properties, it needs to optimize the process for both part geometry and quenching process design. In this work is about obtaining accurate thermal boundary conditions, i.e., HTC distribution. The Medium Carbon steel material model behavior during quenching is to be observed and study the heat transfer characteristics along with changes in microstructure of steel specimen. The data obtained by experimental work will be analyzed and compared with the results from CFD analysis so as to propose the improvement in the existing process to reduce the time and cost with the optimized material properties.

Keywords: **Heat transfer coefficient, distortion, cracking, quenching, tensile stresses, microstructure.**

I. INTRODUCTION

Heat treatment is a method mainly used to alter the physical properties such as microstructure and mechanical behavior, and sometimes chemical properties such as carbon concentration, of a material or a part. There is usually no material removal in heat treatment processes as it is there in the machining processes like grinding or milling. Typical heat treatment processes include those altering physical properties such as quenching, tempering, aging, annealing, normalizing, etc. and the processes which involve chemical property changes such as carburizing, nitriding, etc. This work studies heat transfer, distortion and material property evolution of steel components in polymer quenching. To improve mechanical properties, steel components are usually subject to a heat treatment including quenching. Quenching is a rapid cooling, which prevents low-temperature processes such as phase transformations from occurring. In this rapid cooling process, heat is transferred out from the hot components to the surrounded cool quenching media. A significant amount of residual stresses can be also developed in the component when quenched particularly in water. The existence of residual stresses, in particular tensile residual stresses, can have a significant detrimental influence on the performance of a structural component. In many cases, the high tensile residual stresses can also result in a severe distortion of the component, and they can even cause cracking during quenching or subsequent manufacturing processes.

Li Huiping [2006] et al 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.
Peter Fernandes [2006] et al made an attempt to determine the heat flux transients during quenching of Ø28mm×56mm height and Ø44mm×88mmheight AISI 1040 steel specimens during lateral quenching in brine, water, palm oil and mineral oil and the heat flux transients are Estimated by inverse modeling 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.

Hengliang Zhang etal [2010] Studied the Cooling of steels after the high temperature forming process and its influence on the metallurgical structure and the mechanical properties of the part. From the study it had been cleared that the rate of heat removal from a heated component by a quenchant depends on the ability of the liquid medium to wet and spread on the surface from where heat needs to be removed. Generally Quench hardening is a process which is used to produce steel components with reliable service properties such as high strength, hardness and wear resistance.During quenching of steels Distortion, cracking, distribution of microstructure and residual

Stresses the most common problems. [6]

Ashok Kumar et al [2010] studied the Sensitivity of material properties on distortion and residual stresses during metal quenching processes to investigate the effect of thermal, metallurgical and mechanical properties on the final distortion and residual stresses during metal quenching processes. They use the Finite Element Method (FEM) to solve the coupled partial differential equations while doing this the effects like phase transformation enthalpy, transformation-induced plasticity and dissipation were considered. The curvature and the volume averaged effective stresses were considered for the measurement of distortion and residual stresses, respectively. The sensitivity of the density, specific heat capacity, thermal conductivity, transformation start and end times, martensitic transformation coefficient, martensite start temperature, bulk modulus, shear modulus, yield strength and hardening modulus were the main concern in this work. It is found that reduced metallurgical properties, yield stress, and bulk modulus simultaneously lower the distortion and residual stresses for an equal cooling.

A. Buczek et al [2014] 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.

Present work focused on simulation of quenching process of EN09 rollers for Quenching medium as ethylene glycol aqueous solution for different concentration. Objective of this work is to obtain temperature at different interval of time at different location to plot cooling curve for different quenching medium. Also we are going to obtain HTC for different medium interaction and effect of concentration of ethylene glycol on HTC. Temperature difference between core and surface of specimen can also be obtained from simulation which is useful for prediction of residual stress formation.

The steps taken in the present experimental work are as:

Samples of medium carbon steel with length 100mm and diameter 50mm are cut from metal bar and some samples are prepared for metallographic tests for the measurement of different parameters.

Hardness and toughness are measured and the Microstructures are observed.

The heat treatment process is then carried out in the furnace at 900^0C temperature followed by polymer quenching with different concentrations i.e. 10%, 20%, 40% and 60% of ethylene glycol in water by mass.

The variation of temperature with respect to time is measured for each of the concentration.This data is used for the study of variation in HTC with different concentrations.

The properties Hardness and toughness were measured after heat treatment and the microstructure is observed. The different readings obtained during the experimentation are used to plot the graphs.

II. EXPERIMENTAL WORK

2.1 Assumptions

Material of specimen as well as fluid for medium are considered homogeneous. Properties of fluid changes with respect to temperature. Latent heat of phase change solid – solid of specimen material is neglected as it has very minor significance considering the whole process.Domain boundaries are considered to be continuously expanding and hence heating of medium due to boundary is neglected.Initially fluid is considered at zero velocity i.e. no convection at start of trial. No agitation is provided to specimen.Temperature at start of trial is uniform for liquid as well as for solid specimen.

2.2 Material composition

TABLE 1: MATERIAL PROPERTIES OF EN 09 STEEL

No	Constituent	%
1	Carbon	55%
2	Manganese	9%
3	Phosphorous	0.04%
4	Sulphur	0.05%
5	Iron	Remaining

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

Application

EN09 steel is used as roller in chain conveyor. In this case there is line contact during operation. The purpose of heat treatment is to increase the hardness of surface so as to reduce wear rate of the rollers. As higher cooling rate introduces a lot difference in cooling of surface and core so our purpose is to study the heat transfer characteristics during quenching and find the effect of different concentrations on it.

Solid specimen boundary conditions:
At t =0 sec, Ts = 1173 k
Quenching medium initial temperature: 298k
Fluid domain size: 30cm X 30cm X 20cm
Fluid domain Boundary Condition: Tm= 298k, P = 1.013 bar

2.3Heat Treatment of Specimens

Additional specimens are also made for measuring the toughness and hardness before and after Quenching. Heating is done by using muffle furnace for all specimens by heating to 900^{o}C for 15 minutes and then quenched in the aqueous solution of ethylene glycol with different concentrations i.e.10%, 20%, 40% and 60% of EG in water by mass, finally cooling in open air. The temperature range and hardening/tempering soaking times for the experimental investigations were selected based on the material composition of the specimens. The variation in temperature during quenching is measured by using K type thermocouple. After cooling process the specimen are grinded and polished. Next phase is etching by using mixture of nitric acid and methanol and then the microstructures of the specimens before and after heat treatment have also been observed using microscope.

III. METALLURGY OF PROCESS

3.1 Metallographic tests

The specimen of Medium Carbon steel- with the content as (C =55.0%, Mn =0.9.0%, P =0.2%, S=0.05%) is used for the experimental work. The different test samples are prepared for the experimental work as it needs to conduct the hardness and toughness test along with the observation of microstructure. The details of the sample prepared for Metallographic tests, for Hardness and Toughness tests are: Small pieces of equal sizes were cut from raw material bar of Medium Carbon Steel. Arubber bonded abrasive wheel with soft grade is used to cut the specimen.The specimens are then grinded and polishedfor the experimental work.Then the samples were polished with polish papers.

Fig. 3.1 Microstructure (60% EG)

3.2 Impact Test

The cylindrical test specimens of Medium Carbon Steel steel i.e. EN 09 steel of size 100mm length and Diameter of 50mm are prepared from the metal bar of medium carbon steel and undergone for milling and light grinding to obtain the desired finished size. Then a U-notch of depth 2 mm and width of 2 mm has cut on a surface grinder by using a rubber bonded grinding wheel. The impact test was carried out on the on an impact test machine.

3.3 Hardness Test

The same cylindrical sample which is used in impact testing is used for hardness testing. The hardness values before and after heat treatment were measured on hardness tester.

TABLE 2: Hardness readings (In HRc) (60% EG)

Before quenching		After quenching	
Surface	Core	Surface	Core
32	30	51	50

IV. CFD ANALYSIS

The specimen can be modeled by using different CAD software which is compatible with the computational fluid dynamics software. For the current modeling, Pro|ENGINEERWILDFIRE 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.

Pro ENGINEER is a feature-based, parametric solid modeling system with many extended design and manufacturing applications. As a comprehensive CAD/CAE/CAM system, covering many aspects of mechanical design, analysis and manufacturing, Pro|ENGINEER represents the leading edge of CAD/CAE/CAM technology.The model is cylindrical roller with diameter 0.05m and length 0.1m.

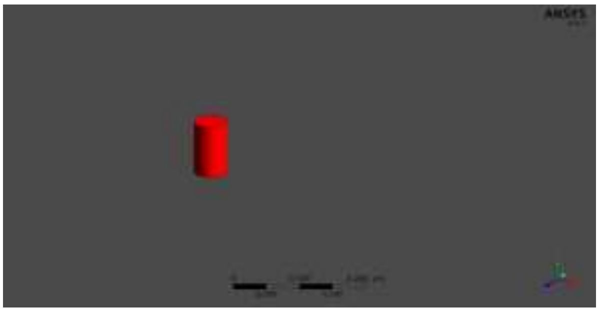


Fig 4.1 3D model of solid specimen

The CFX uses finite element method of Discretization and solving. The model has to be divided down to finite number of parts and processing is done on every part separately. The optimum mesh would therefore, be such that the mesh size is fine in regions where accuracy is important and coarse where accuracy is not so much a matter of concern. The combinations of these give optimum computation time, with fairly good accuracy and lower processing memory.

The model under consideration is critical for accuracy. Hence, we keep the mesh size small. Below the toolbar, select mesh tool chest→ global mesh setup→ seed size 4→ compute mesh. The model after meshing is seen as below

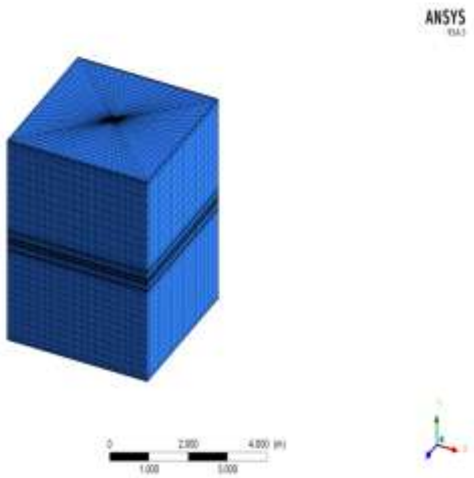


Fig. 4.2 Meshing Of outer domain

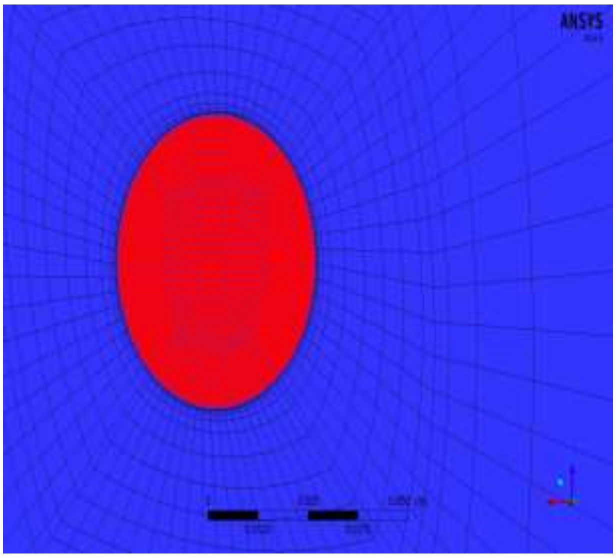


Fig. 4.3 Top view of solid domain

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.

V. RESULT AND DISCUSSION

The thermal performance is analyzed for workpiece to be quenched. Different trials are taken by varying quenching medium with increasing concentration of ethylene glycol by mass. The results obtained are discussed in this chapter.

5.1Temperature vs. Time

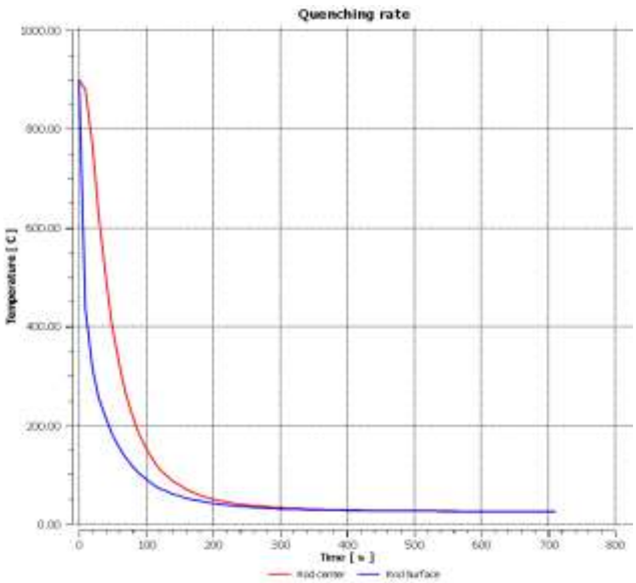


Fig.5.1 Temperature vs. Time for 0% concentration by mass of ethylene glycol

The above graph shows variation of temperature with respect to time for surface and core. We can observe large temperature difference between surface and core of the specimen. Due to variation in cooling of surface and core there will be uneven contraction of material of specimen which is responsible for residual stresses.

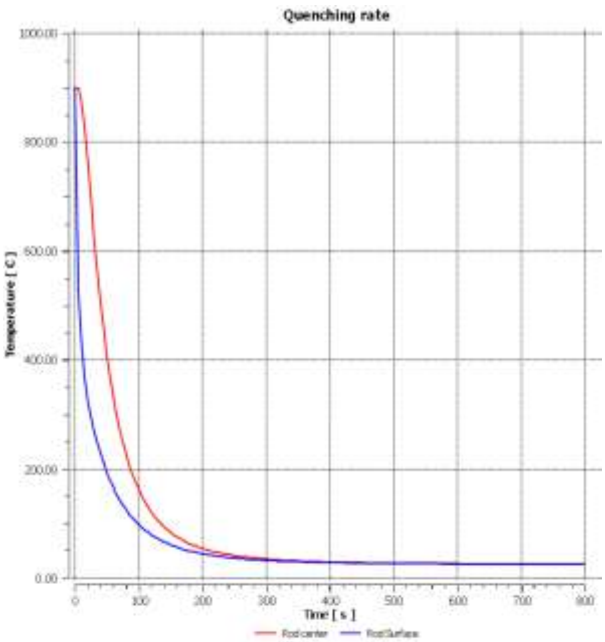


Fig 5.2 Temperaturevs. Time for 20% concentration by mass of ethylene glycol

The above graph shows variation of temperaturewith respect to time for surface and core when quenching medium is 20% ethylene glycol solution by mass. 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.

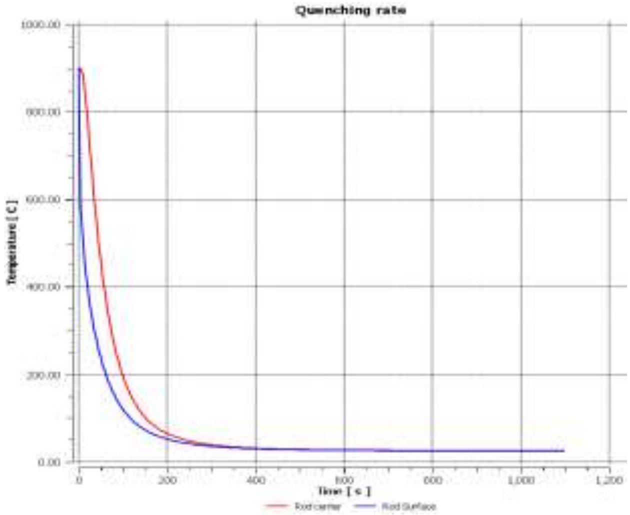


Fig 5.3 Temperaturevs. Time for 40% concentration by mass of ethylene glycol

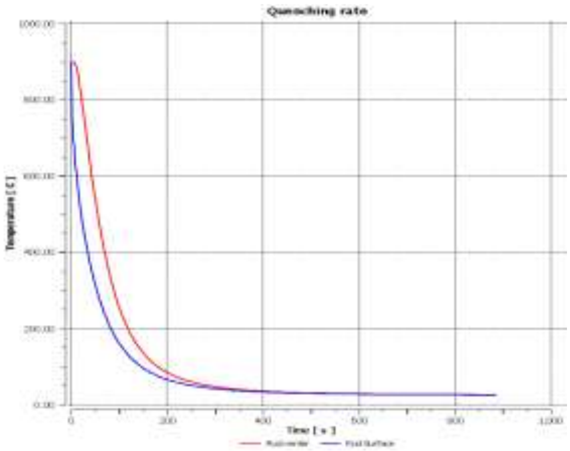


Fig 5.4 Temperaturevs. Time for 60% concentration by mass of ethylene glycol

The above graph 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 percentageof 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.

5.2 Heat Transfer Coefficient vs. Time

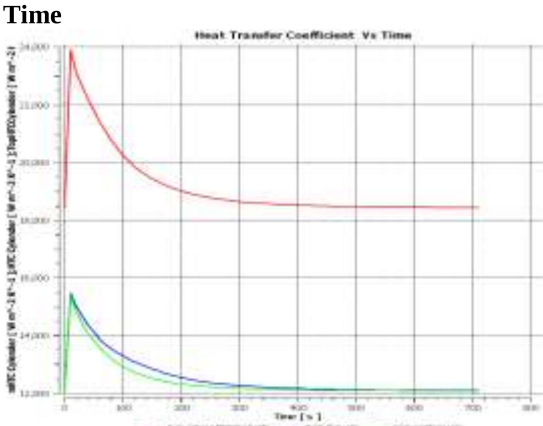


Fig 5.5 HTC vs. Time for 0% Concentration of Ethylene Glycol by Mass

Above graph shows the variation of HTC with respect to time when quenching medium contains 0% concentration of ethylene glycol by mass. Graph shows that HTC is more for curved surface of the cylindrical specimen and it is significantly less for top and bottom surface due to limitations of convection of fluid. This is nucleate boiling phase. During this phase there is evaporation of water and hence heat transfer rate is very high and hence it approaches the maximum value. After that there is formation of film of water vapor around the specimen surface, during this phase there is sudden drop in HTC as water is bad conductor of heat. After few seconds film of water vapor collapses and natural convection starts and HTC almost remains constant.

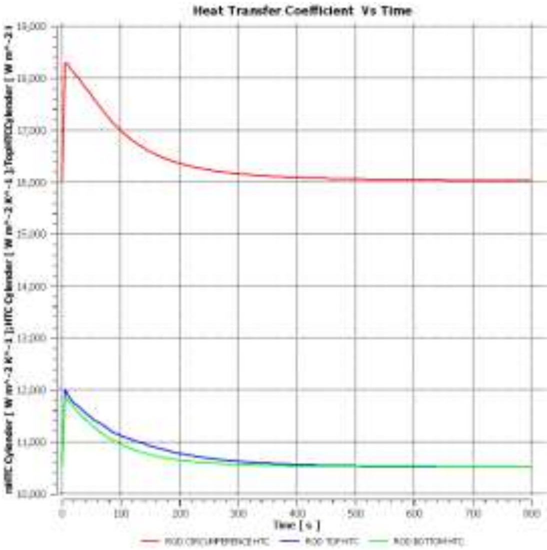


Fig 5.6 HTC vs. Time for 20% Concentration of Ethylene Glycol by Mass

Above graph shows the variation of HTC with respect to time when quenching medium contains 20% concentration of ethyleneglycol by mass. The graph shows similar nature as that of the previous condition. But due to addition of 20% ethylene glycol solution HTC decrease and it approaches maximum value 18.4 kW/m^{2}k. We can predict that addition of ethylene glycol reduces the HTC during quenching process and ultimately reduces the cooling rate of the specimen.

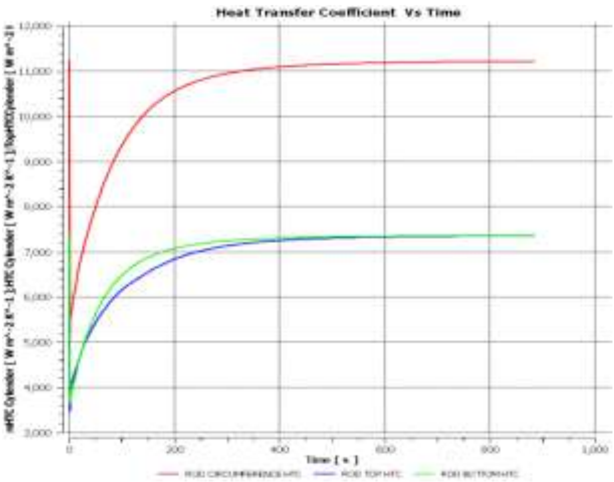


Fig 5.7 HTC vs. Time for 60% concentration of ethylene glycol by mass

Above graph shows the variation of HTC with respect to time when quenching medium contains 60% concentration of ethyleneglycol by mass. The graph shows same nature as that of previous case. During this trial percentage of ethylene glycol is significantly higher which is responsible for lower HTC. As percentage of ethylene glycol increases HTC decreases which results in lower cooling rate. As percentage of ethylene glycol increases the heat transfer from surface t of specimen to quenching mediumapproaches the heat transfer by conduction from core to surface of specimen, as a result of this temperature gradient between core and surface of medium decreases and there is less amount of residual stress formation.

5.3 Temperature Plots

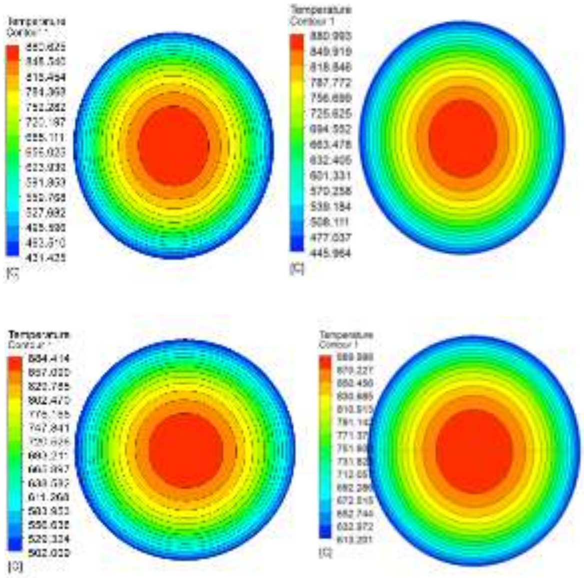


Fig.5.8 Temperature Distribution along Horizontal Section at Different Concentration after 10 sec.

Above plots shows the temperature distribution of specimen on horizontal plane after 10 sec. We can observe that as concentration of ethyleneglycol increases the temperature gradient decreases. So we can predict that residual stresses induced will decreases as concentration of ethylene glycol increases.

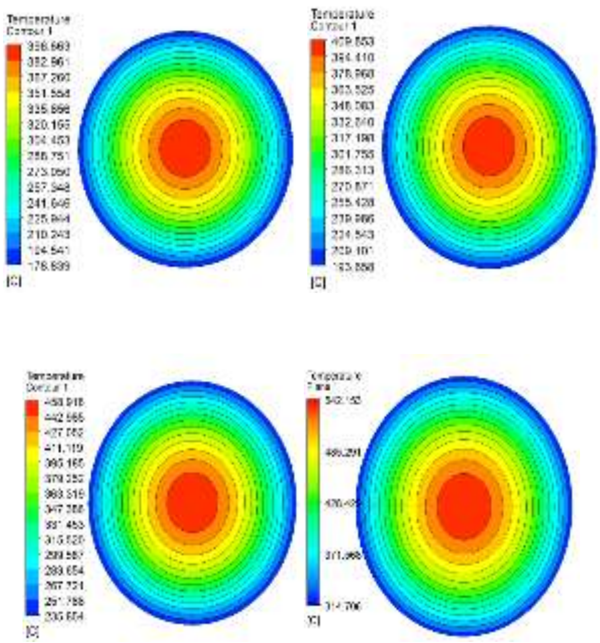
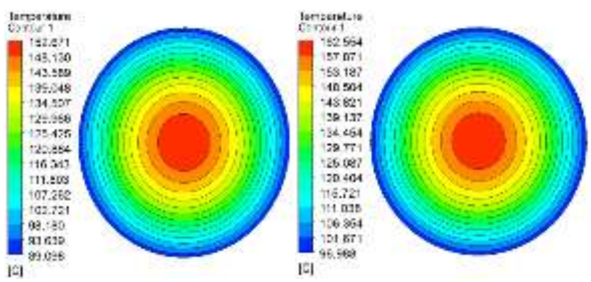


Fig. 5.9 Temperature Distribution along Horizontal Section at Different Concentration after 50 sec.



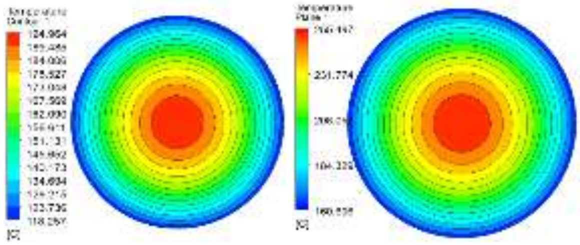


Fig. 5.10 Temperature Distribution along Horizontal Section at Different Concentration after 100 sec.

VI. CONCLUSION

Based on the outcomes of the heat treatment and quenching process investigations performed on medium carbon steel, the conclusions are:

1) Due to variation in cooling of surface and core there is uneven contraction of specimen which may results in residual stress.
2) As the concentration of ethylene glycol is increased, Temperature variation between surface and core during quenching is decreased results in less stress.
3) As percentage of ethylene glycol is increased the heat transfer rate from the surface is decreased.
4) HTC is more for the curved surface of specimen as compared to top and bottom.
5) Due to addition of ethylene glycol HTC decreases.

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