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SIMULATION OF QUENCHING PROCESS BY NUMERICAL HEAT TRANSFER MODEL

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ABSTRACT

In quenching process many parameters have an effect on this process such as steel type, quenching medium type, quenching medium temperature and the volume of the workpiece. In order to give a workpiece free of defect, it's very important to understand the effect of these parameters on this process.

In the present work a mathematical heat transfer model have been used to simulate the heat treatment (quenching process). This model used to investigate the temperature distribution in the workpiece at different time. A numerical scheme based on a control volume formulation and a computer program with C++ language was used to solve the set of heat transfer equations. The developed model was used also to evaluate the effect heat treatment parameters such as quenching media, carbon steel type and cross sectional area of the workpiece. The model also can be used to simulate the heat treatment process (quenching process) of various materials and alloys with different conditions.

The results of the model were compared with experimental published data give good agreement.

Key word: Quenching, heat transfer, mathematical model.

الخلاصة

هنالك عوامل كثيرة تسيطر على عملية الاصلاد بالتقسية والمنتج من هذه المعاملات ومن اهم هذه العوامل هي نوعية الفولاذ او نوع المعدن ، نوع وسط التبريد ودرجة حرارته وكذلك حجم القطعة المعاملة حراريا.لذلك من الضروري جدا معرفة تاثير هذه العوامل للحصول على منتج خالي من العيوب قدر الامكان وباقل جهد عملي.

في هذا البحث تم وضع انموذج رياضي لوصف عملية الانتقال الحراري خلال عملية الاصلاد بالتقسية لانواع مختلفة من الفولاذ ، حيث تم استخدام هذا الانموذج المقترح لمعرفة وفحص توزيع درجات الحرارة في القطع المعاملة حراريا وتاثير العوامل المذكورة في اعلاه وبالفترات الزمنية المختلفة. تم استخدام الطرق العددية لايجاد الحلول النهائية للمعادلة الخاصة بابانموذج الرياضي وكذالك تم بناء برنامج بلغة الـ C++ لايجاد الحلول لهذه المعادلات.

باستخدام هذا النموذج تم دراسة تاثير العوامل التي تتحكم بالمعاملات الحرارية بصورة عامة وعملية الصلاد بصورة خاصة وقد استخدم هذا الانموذج ايضا بدراسة عملية الاصلاد لمعادن اخرى غير الفولاذ حيث اظهرت المقارنة بين نتائج البحث الحالي مع نتائج عملية منشورة اظهرت تطابق جيد بينهما.

1-INTRODUCTION

Heat treatment known as a combination of heating and cooling process, it's used to improve the mechanical properties of metals and its alloys i.e. ductility, hardness, yield strength and Impact resistance. The mean deference between the types of this process is the cooling rate after the heat, for example the anneling process used slow cooling rate and the quenching process use high cooling rate. Quenching is one of the most important heat treatment for carbon steel and alloys steel, in this process the workpiece is heated to the temperature depending on the chemical composition or carbon percent of the workpiece, then cooling rapidly in media such as oil or water almost, during this heating and cooling cycle many defects may be occur such as internal stresses, distortion and cracks thus we have to reduce this defects as possible.

In fact the variation in the temperature distribution with time through the workpiece is the most important factors which is responsible for these defects, for example we have to reduce the thermal gradient in the workpiece in order to reduce the thermal stresses which occur due to high thermal gradient during the cooling process, as wall as to give a uniform phase transformation and uniform mechanical properties such as hardness, ductility and strength.

So it's very important to study the temperature distribution and the parameters which effect on the cooling process, from other side by understanding the relationship between the treatment parameters and temperature distribution the phase transformation during the process will be under the control.

G.Sanchez Sarmiento [1] carried out a comparative study has been done to simulate the quenching process for 7075-T Aluminum alloy and to predicate the residual stresses, and heat transfer coefficient. A standards finite element software called ABAQUS was use in the study and INC-PHATRAN code means was use to calculate the heat transfer coefficient as dependent of the temperature.

A further work was carried out by J.Trazaska [2] to simulate the heat treatment process; in this work a computer program was developed to predicate the steel properties after heat treatment process. T. Madhiyanon etal [3] developed a two mathematical models of quenching heat treatment, the first model is based on one dimensional and the second model is two dimensional model based on cylindrical coordinates with similar assumption to the first model. Brandon Elliott B. [4], study the thermal stress and distortion which is occur during the heat treatment process (quenching). A computer software **DANTE** used in this studies to evaluate the temperature distribution, the calculation of the temperature depends on the heat transfer coefficient on the surface of the modeled part, experimental work have been carried out in this work to verifying the theoretical work.

In present work a mathematical heat transfer model has been used to simulate the heat treatment (quenching process). This model used to investigate the temperature distribution to the workpiece at different time. A numerical scheme based on a control volume formulation and a computer program with C++ language was used to solving the set of heat transfer equations. The developed model was used also to evaluate the effect heat treatment parameters such as quenching medial, carbon steel type, and cross sectional area of the work pace. The model also can be used to simulate the heat treatment process of various materials and alloys with different conditions.

2-THEORITCAL CONSIDERATION

In the last few years a mathematical and computer simulation were used in the manufacturing process and heat treatment process extensively to reducing the efforts in this process.

A computational 2D-unsteady state heat transfer model has been used simulate the heat treatment process. The thermal material properties, i.e. thermal conductivity, specific heat, density are temperature dependent the heat transfer coefficient also taken as a temperature dependent.

2-1- Mathematical Model

The transient temperature distribution (T) of the heat treatment workpiece is a function of time (t) and a coordinates x,y, the governing equation for conductions heat transfer is

$$\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)=\rho C_p\frac{\partial T}{\partial t} \tag{1}$$

The following assumptions are made in this model.

1-The temperature of the quenching media is not affected by workpiece temperature during the quenching process (constant value).

2-The maximum variation in the temperature distribution is taking place across the cross sectional area (X-Y) plane.

2-2- Boundary Conditions

Fig.1 shows the geometry of the workpiece used in the analysis and the general boundary conditions, we can describe this boundary as follows.

1-T (x,y,t=0) = To (x,y) =T_q of heat treatment which is dependent on the type of carbon steel

2-x=0 ; $0 \le y \le (b/2)$ and y=0 ; $0 \le x \le (a/2)$.

$$k\frac{\partial T}{\partial x}=\frac{\partial T}{\partial y}=h_c(T-T_m)$$

3-x=a/2 ; $0 \le y \le (b/2)$ and y=b/2 ; $0 \le x \le (a/2)$.

$$k\frac{\partial T}{\partial x}=\frac{\partial T}{\partial y}=\text{zero (adiabatic)}$$

The general equation (1) must setup at each point in the domain, this equation is modified to incorporate boundary conditions so that we have set of equation.

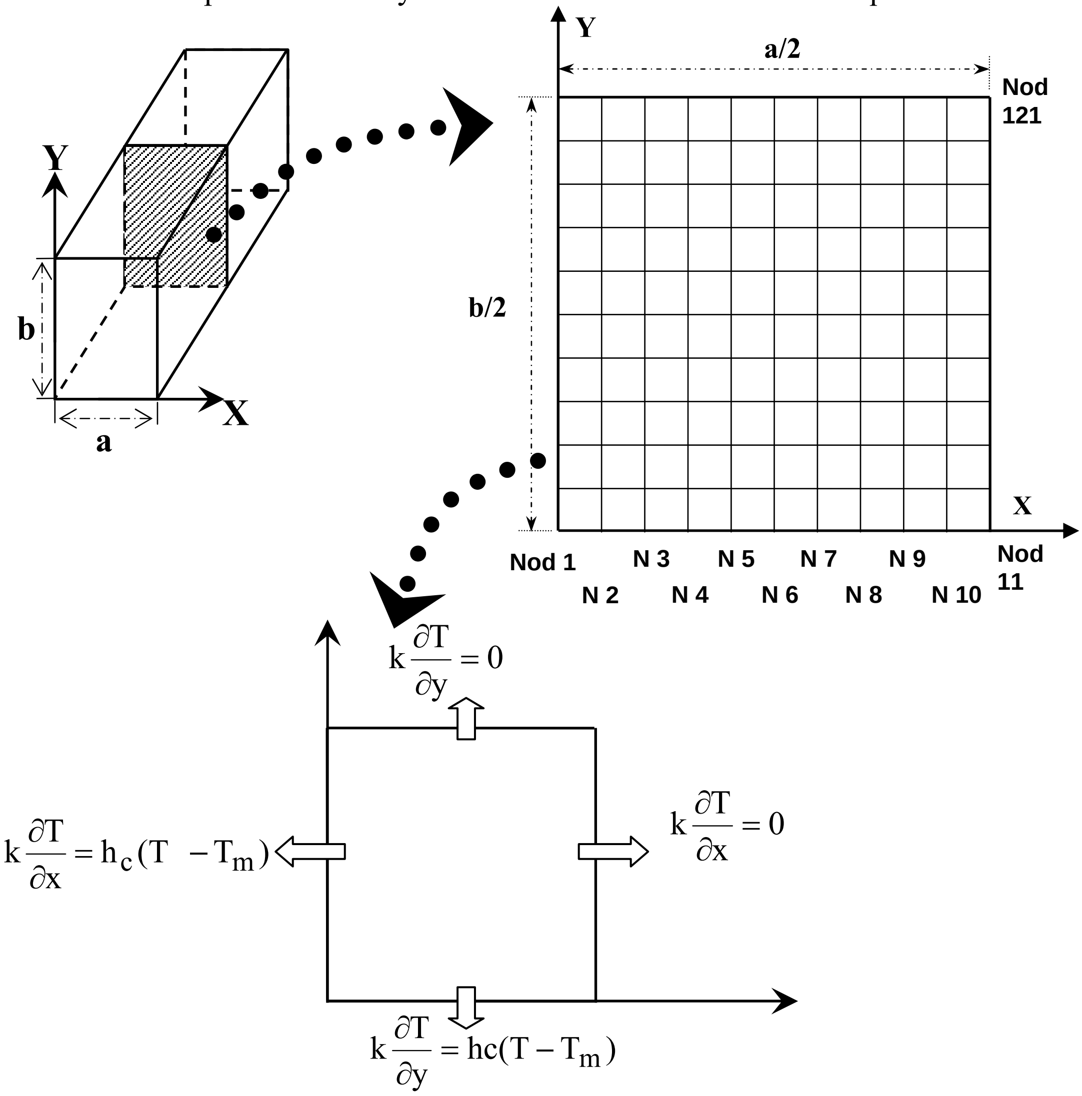


Fig.1 -The cross sectional area with nodes and boundary conditions.

2-3 Numerical Data

The thermal and physical material properties for the steel which used in the present work are listed in **Table 1** this data are taken from [5], this properties variation with temperature and carbon percent or chemical composition, from this table we can see that the thermal properties is temperature dependent more than carbon steel type.

Table (1) -A-Thermal conductivity (W/m^o.C) of steel, type 1008 and 1030 at different temperature. [5]

K \ T ^{o}C	0	100	200	300	400	500	600	700	800	1000	1200
1008	59.5	57.8	53.2	49.4	45.6	41	36.8	33.1	28.5	27.6	29.7
1030	53.5	52	49.5	46.7	42.9	39.4	35.6	31.8	26.8	27.2	29.7

Table (1) -B-Specific heat (J/kg^o .C) of steel, type 1008 and 1030 at different temperature. [5]

Cp \ T ^{o}C	50-100	150-200	200-250	250-300	300-350	350-400	450-500	550-600	650-700	750-800	850-900
1008	481	519	536	553	574	595	662	754	867	875	846
1030	486	519	532	557	574	599	662	749	846	950	

Table (1) -C-Density (kgm^{-3}) of steel, type 1008 at different temperature.

ρ \ T ^{o}C	0	100	200	300	400	500	600	700	800	1000	1200
1008	7880	7880	7800	7790	7760	7670	7600	7580	7520	7390	7300

In this work the value of heat transfer coefficient is dependent on the temperature and quenching media type see **Table 2.**

Table (2) The heat transfer coefficient for the water and oil quenching. [4].

T ^{o}C	h_c water (w/m^2.C)	h_c oil (w/m^2.C)	T ^{o}C	h_c water (w/m^2.C)	h_c oil (w/m^2.C)
50	500	50	500	9000	5000
100	1000	70	600	6000	4750
180	4000	100	700	4000	2000
200	8000	500	750	3000	1300
300	10000	1500	800	2000	1150
350	11000	1750	900	1000	800
400	10000	2000	1000	1000	780

450	4000	4000			

In the heat treatment process the value of heat treatment temperature (quenching temperature) is a function of chemical composition or carbon steel type, thus we have to describe the relationship between the quenching temperature and carbon percent to use in the model as follows:

1- Carbon steel which content **0.8 ≤%C≤1.9.**

Quenching temperature **(T_q)=753 ^oC.**

2- Carbon steel which content **0 ≤%C≤0.8.**

T_q= [(910-233.75×%C)+ 30] ^oC [present work]

After we described the heat transfer model in the previous section and the numerical data which is need we will used a numerical scheme based on a control volume or finite volume approach which consists three steps the first is the grid generation and the second is discretization (to the internal and boundary equation) and finally the solution of the equation, iterative method known as (TDMA) have been used to solve the system of equations [6, 7].

A computer program employed the C++ language was constructed to found the solution of the algebraic equations system this program taken in account the effect of heat treatment process in general and (quenching treatment) in special case, i.e. quenching media, type of carbon steel and the cross sectional area of the workpiece.

3- RESULTS AND DISCUSSIONS

In the previous section we say that the proposed model can be use to simulate the quenching process of different materials and alloys no, and the material type is an input data to the model, so that to checkup the results of this model a comparison between the experimental data reported by [1] for the 7075-T6 AL-Alloy and the present model have been carried out, the results are presented in **Fig.2** showing good agreement.

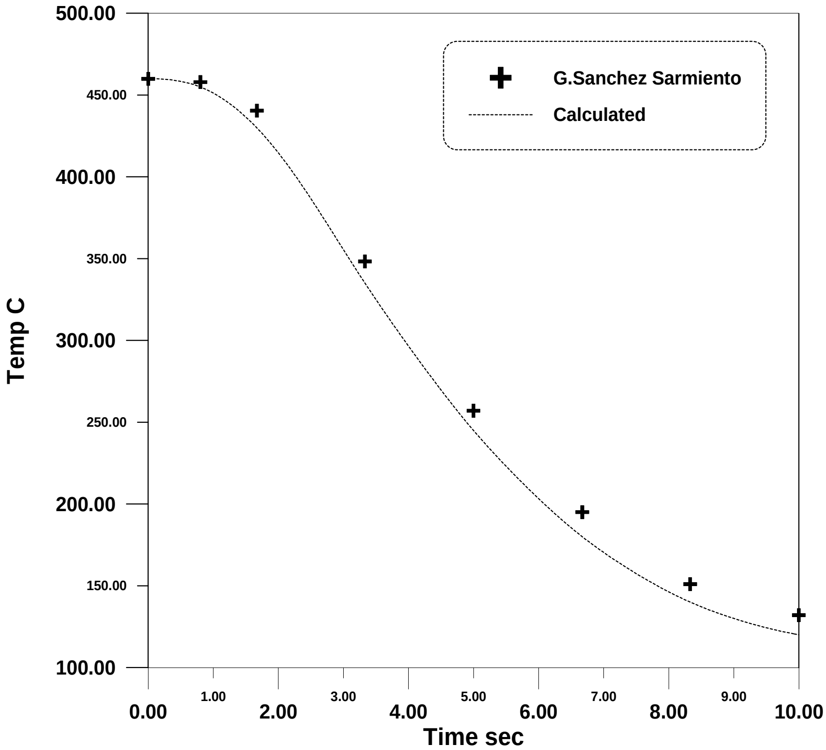


Fig. 2 -A comparison between the present model and experimental data by [1]

Different cases have taken to study the effective parameter in the quenching treatment as shown in **Fig. 3**

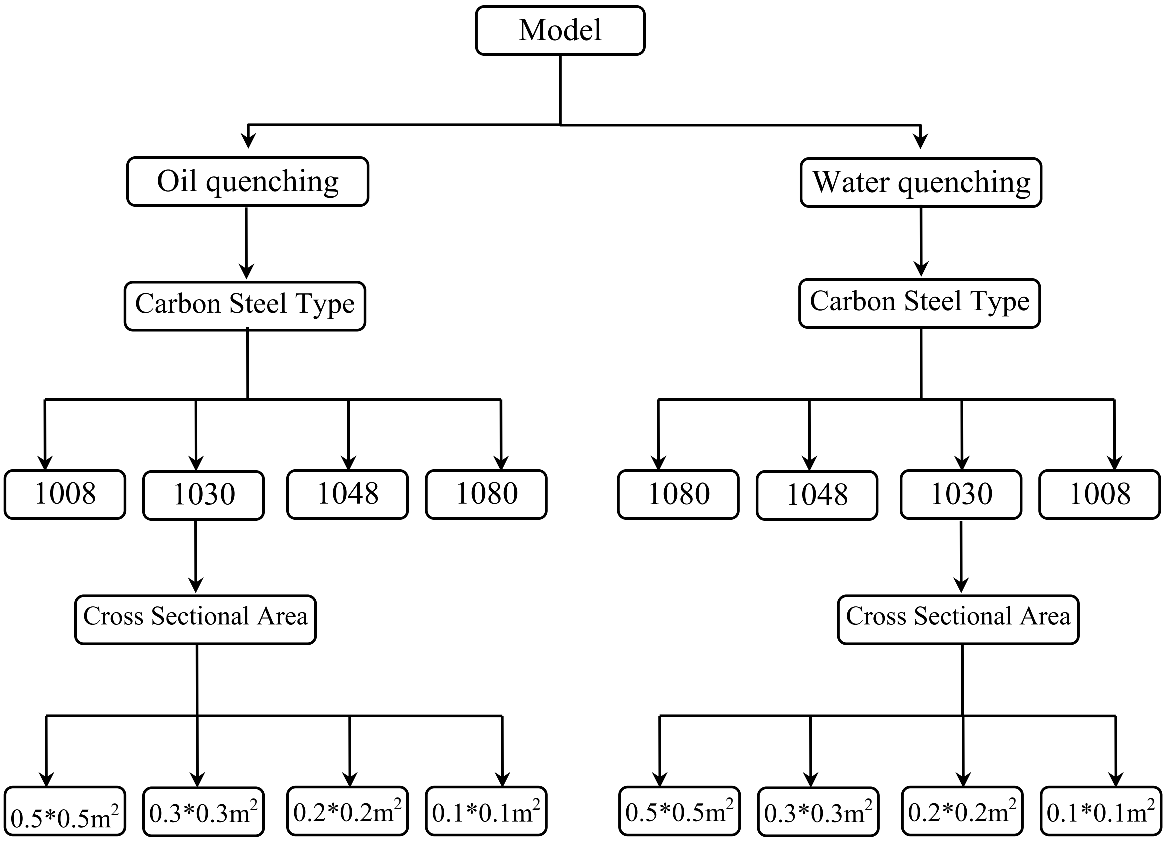


Fig. 3. The case studies by the present model

The results of the suggested model are presented in figures which is show in the next paragraphs. **Fig.4** shows the temperature profiles for the carbon steel **1008 AISI SAE** grade, to the workpiece have a cross sectional area equal to 0.2×0.2 m^2 quenching in oil, from this figure we can see that the thermal gradient across this area is increase with time during the quenching treatment, but in time more than 300 sec this gradient will decreasing. Thus it's very important to make the time of cooling step between the start and the end of cooling process under the control to reduce the thermal gradient as possible as to reduce the thermal stress which is occur during this time.

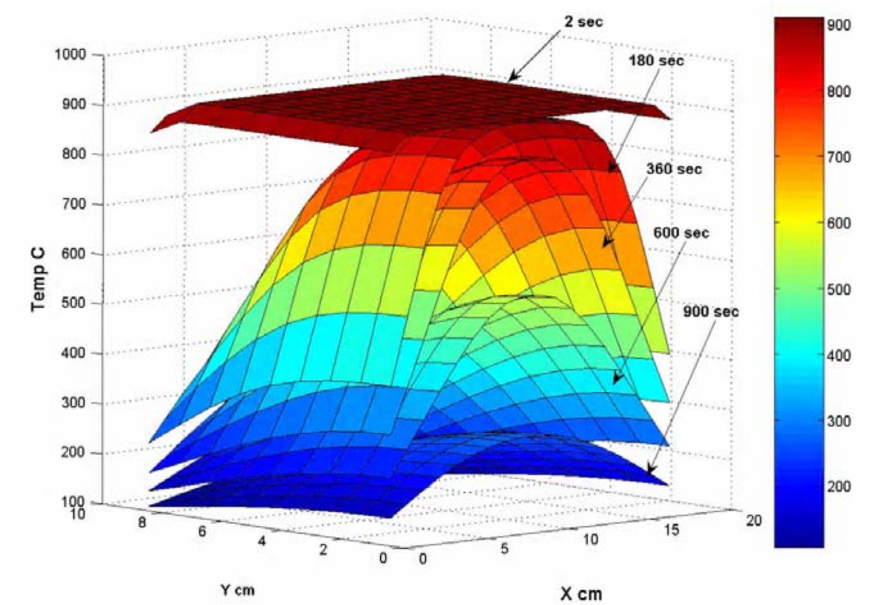
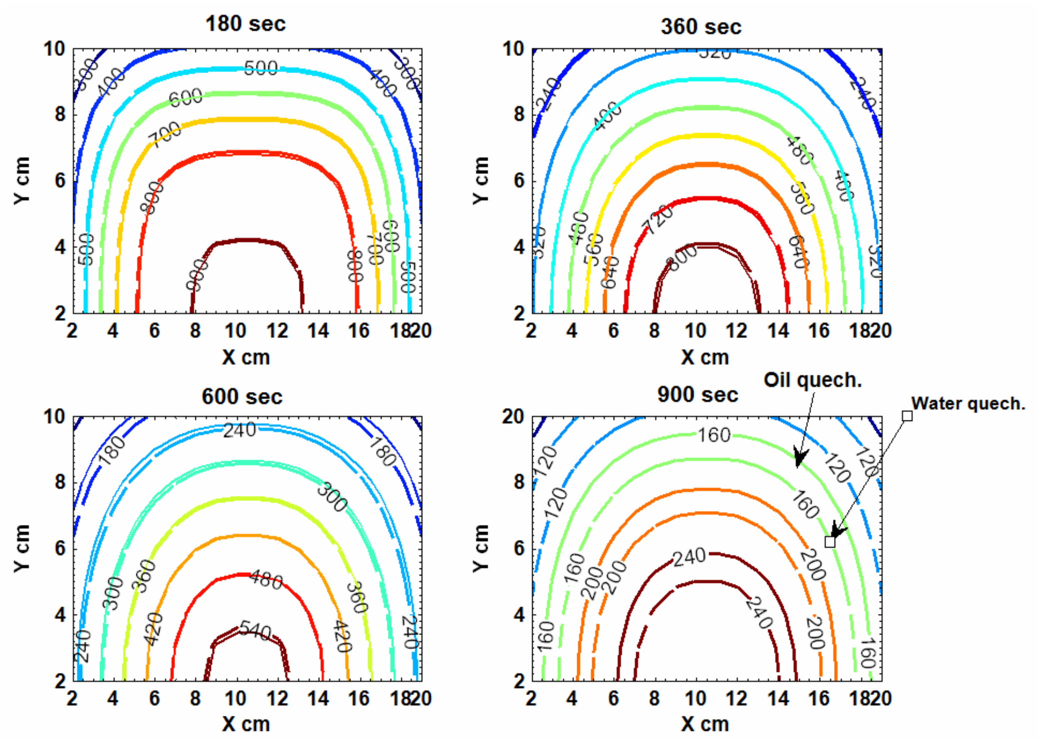


Fig. 4.Temperature distributions, Cross Sectional area 0.2×0.2, Steel Type 1008, Oil Quenching.

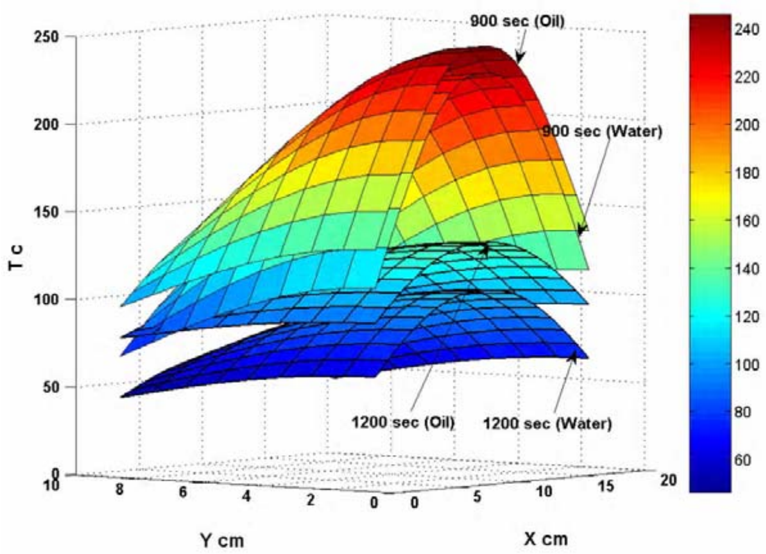
Fig. 5-A and B shows the effect of quenching medium on the temperature distribution and thermal gradient at different time (180, 360, 600, 900 and 1200) sec. From this figure we can see that the quenching medium is not effective in time less then 300 sec, after this time (more then 300 sec) this effect be a clear see Fig.5- B.

Fig.6 A, B, C and D show the effect of carbon steel type (1008, 1030 and 1080) on the thermal distributions and the thermal gradient at different time, these figures show that the difference between the maximum temperature in for the workpiece is increase with increasing the time of the cooling process and when the carbon steel type or carbon percent increase, the same behavior for the thermal gradient can bee seen also.

Fig.7 shows the changing in temperature with time at different quenching medium (oil and water) for the node no 1, 11 and 121, from this figure we can see that the maximum cooling rate is in node 121, corner node, and the minimum is for the node 1 the center of workpiece.

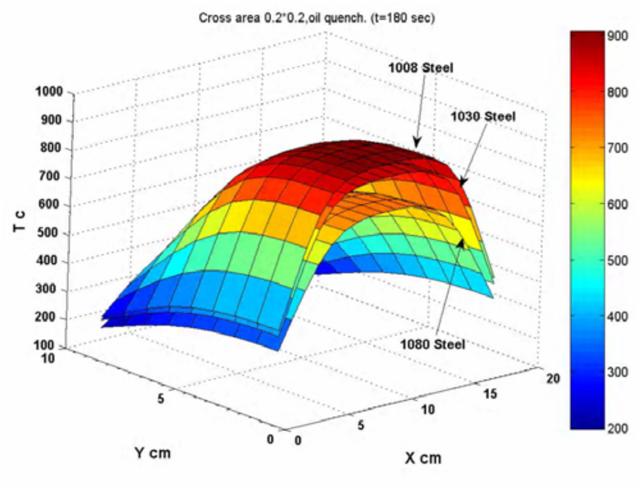


-A-

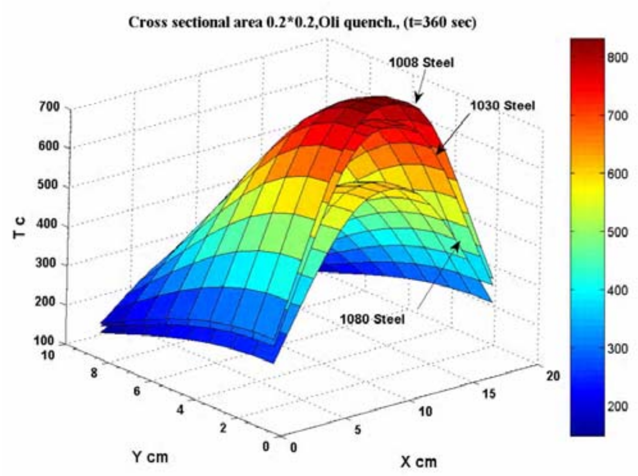


-B-

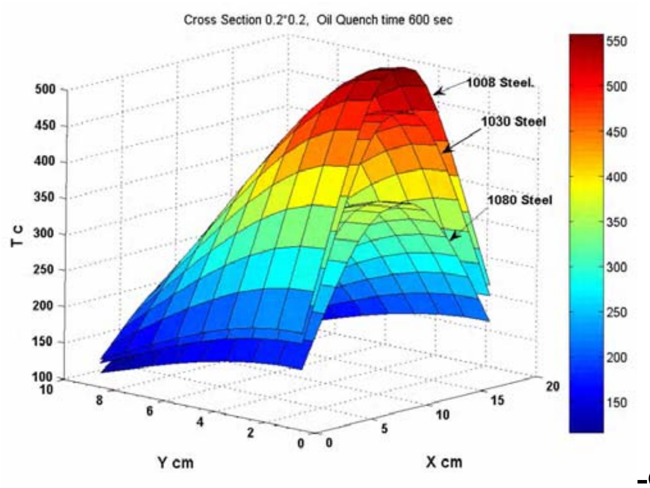
Fig. 5- The effect of quenching medium on the temperature distributions, Cross Section 0.2×0.2, Steel Type 1030



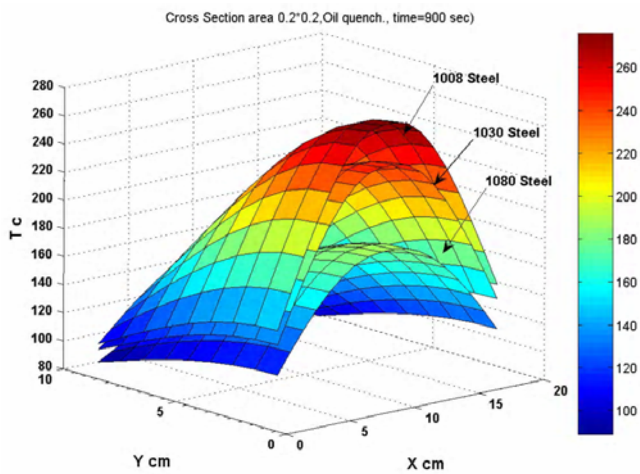
A- after 180 sec



- -B- after 360 sec



-C- after 600 sec



-D- after 900 sec

Fig. 6 The effect of carbon steel type on the temperature distributions, Cross Section 0.2×0.2, Oil quenching.

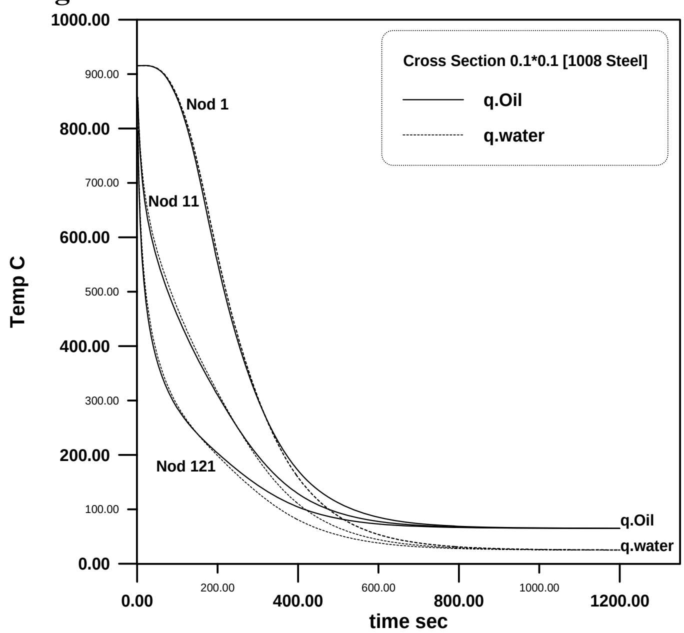
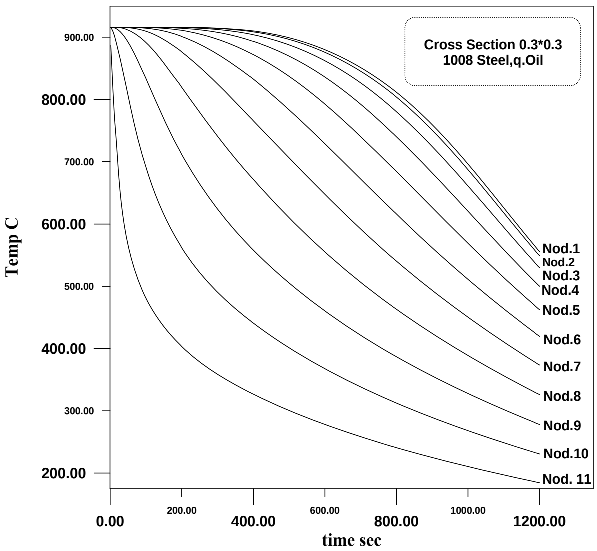


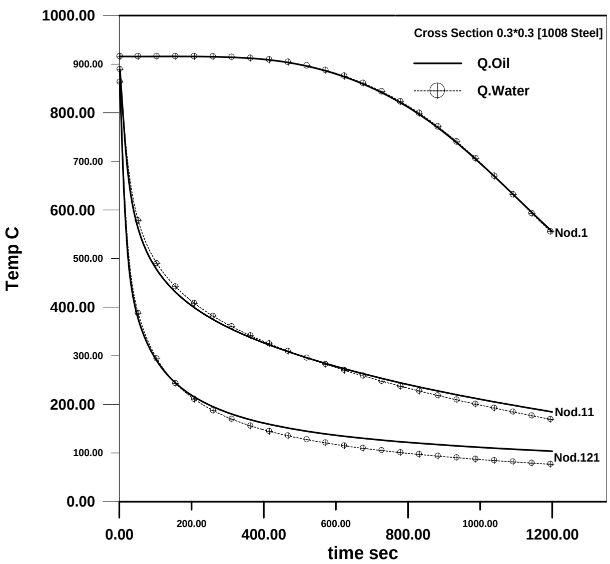
Fig.7 Temperature vs. time using two quenching media (water and oil), for Nodes 1, 11 ,121.

Another cases show in **Fig.8-A, B, C** in this case a workpieces with cross sectional area equal to 0.3×0.3 m^2 and steel type 1008 quenching in oil. **Fig.8-A-** shows the temperature profile for the sets of nodes from node no 1 to node no 11 (the center line of work pace). The other figures B and C show the same behavior even the other parameters changed i.e. quenching media and carbon steel type.

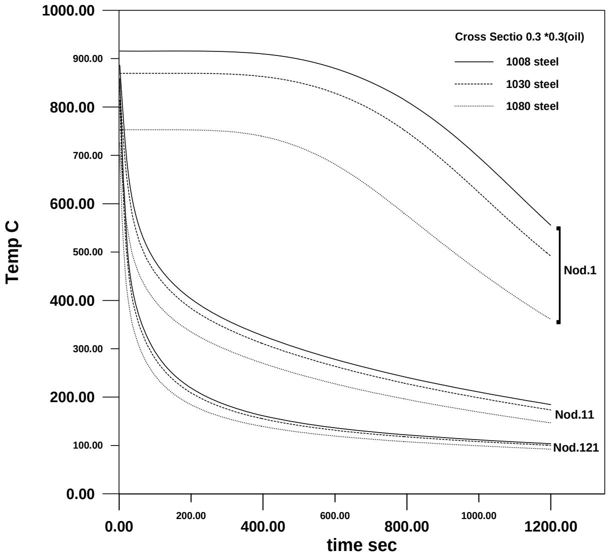
Fig.8-B shows the effect of the quenching medium on the temperature profile, while **Fig. 8-C** shows the effect of carbon steel type on this profile, in fact we can see that the effect of steel type more then quenching medium.



A- Nodes from 1 to11



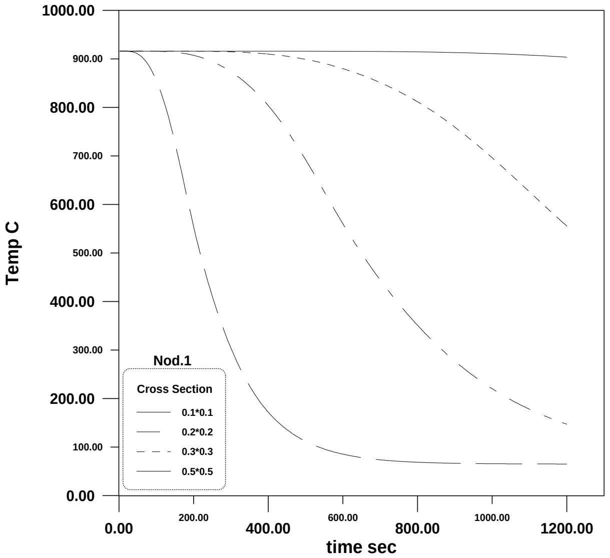
B- Nodes 1, 11 and 121.



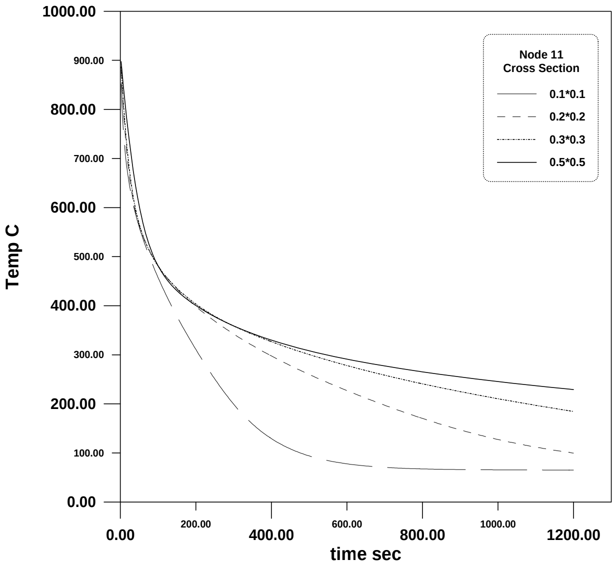
C-Nodes 1, 11 and 121, different carbon steel type.

Fig.8 - Temperature vs. time.

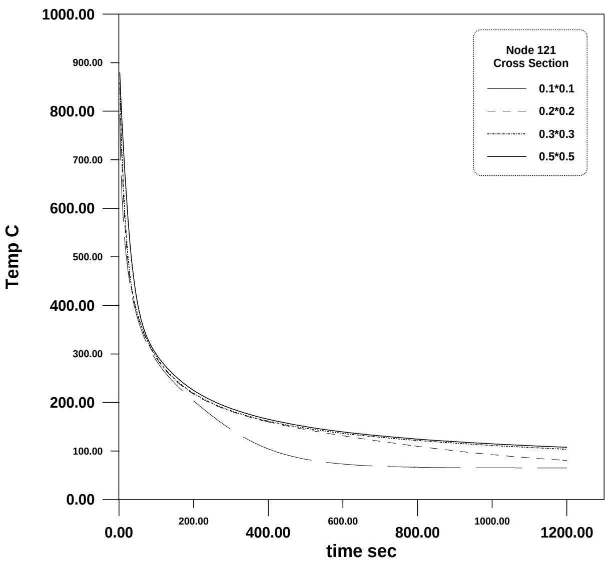
Finally we will study the effect of cross sectional area on the temperature distribution. **Fig.9 A, B, C** show these effects, from this figure we can see that the maximum difference in temperature occur in the center of the workpiece (Node 1), see **Fig.9 A**, wile this difference is not appear for nodes near from the surface of the workpiece see **Fig.9 B, C**.



A- Node 1



B- Node 11



C- Node 121

Fig.9- The effect of cross sectional area on the temperature profile to the 1008 carbon steel type.

4-COUNCLUSTIONS

1-The results of the present work have good agreement with other experimental published data (experimental data reported by [1] for the 7075-T6 AL-Alloy).
2-The quenching medium is not affected on the temperature distribution or thermal gradient in the first time of cooling process so, but after this time the quenching medium have high effect.
3-We can reduce the thermal gradient by use different quenching medium or by use cycle of quenching medium. This case can be used especially for the workpiece with high cross sectional area.
4-Increasing the quenching temperature lead to increasing the thermal stress which is occur during the quenching process. So that it's very important to reduce the quenching temperature as possible as.

LIST OF SYMBOLS

C_p Specific heat of metal, (J/kg.^{o}C).
h_c Coefficient of heat transfer (w/m^2. ^{o}C).
K Thermal conductivity of the metal, (w/m. ^{o}C).
T Temperature, (^{o}C).
T_o Initial temperature , at time equal to zero, (^{o}C).
T_q Quenching temperature, (^{o}C).
T_m Temperature of quenching medium, (^{o}C).
t Time, (sec)
x,y Coordinate axis to the cross sectional area of workpiece

REFERENCES

1-G. Sánchez Sarmiento , D. M. Coscia 1, C. Jouglard , G.E. Totten ,G.M. Webster and J. Vega "**Residual Stresses, Distortion and Heat Transfer Coefficients of 7075 Aluminum Alloy Probes Quenched**"
getottenassociates.com/ pdf_files/HT MOD
2- J. Trzaska, L.A. Dobrzański, A. Jagiełło," **Computer programme for prediction steel parameters after heat treatment**" journal of Achievements in Materials and Manufacturing Engineering , VOLUME 24, ISSUE 2, October 2007
3-T. Madhiyanon, A. Techaprasan, S. Soponronnarit "Mathematical model based on heat transfer and coupled heat and mass transfer for rapid high temperature treatment in fluidized bed : Application for Grain Heat Disinfestations "
4- Brandon Elliott Brooks and Christoph Beckermann " **Prediction Of Heat Treatment Distortion Of Cast Steel C-Rings** "In proceedings of the 61st Technical and Operating conference. SFSA, Chicago, IL. 2007.
5- ASM Handbook, Volume 1, "**Properties and Selection: Irons, Steels, and High Performance Alloys**" 2005
6-Suhas V. Patanker " numerical heat transfer and fluid flow " Hemisphere publishing, 1982.
7-H. K. Versteeg and W. Malalasekera "**An Introduction to Computational Fluid Dynamics**" the Finite Volume Method, Longman Group, Ltd. 1995