Numerical Evaluating Study of the Thermal Initiation Time of Sample Affected by Applied Thermal load

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Abstract

The thermal initiation time of samples affected by thermal load applied on both faces of the samples was studied numerically using ANSYS-14 during the unsteady heat transfer. Three samples of different lengths (10, 20 and 30) cm were selected, with a constant height of 2.5 cm. Three materials with different thermal properties were selected (high thermal diffusivity (α), medium thermal diffusivity and a low thermal diffusivity) and applied to all three samples. The three samples were subjected to a constant thermal load of 100 °C on one face and the other face to a thermal load of 25 °C. The thermal initiation time of samples was adopted when the temperature of the selected points reached 26 °C, which is 1°C higher than the initial conditions, which can be adopted as a measure of conductivity, and represents the material's response to the heat on it. The aim of this study is to know the thermal initiation time of samples of different lengths, and materials with different thermal properties at a number of points along the samples at the beginning , the middle and the end as a first study .The second study focused on the adoption of a fixed distance(x) from the hot face for all lengths of samples at a number of points with x = (1, 3, 6 and 9)cm. The results of the first study showed that the thermal initiation time of samples increases with the increase of distance from the hot face and the relationship between them was an exponential positive relationship when fixed the thermal diffusivity. The study also showed that the relationship between the thermal initiation time of samples and the thermal diffusivity was an exponential inverse relationship when the distance from the hot face was fixed. The thermal initiation time of the chromium material with the highest diffusivity at 26 °C ranged from (0.0465 - 207.28) seconds and the low-diffusivity cellular glass material ranged between (3.348 - 21762) seconds to the nearest and farthest point from the hot face. The result of the second study showed that the length of the sample has no effect on the thermal initiation time of sample at the equivalent points located on a fixed distance from the hot face.

Keywords: Thermal Diffusivity (α), Unsteady Heat Transfer, Thermal Initiation Time of Sample, Thermal Properties, Numerical methods for heat transfer.

Nomenclature

T.I.t	Thermal initiation time
α	Thermal diffusivity
R	Root mean square

Introduction

Heat is transferred from one point to another due to temperature difference between them. There are also other variables that contribute to increase or decrease the rate of heat transfer between these two points, such as the thermal properties of the material or materials exposed to the heat effort, and the shape of the sample and its dimensions affect the amount of heat transferred. The amount, shape and distribution of pores within the material also has a role in it.

Part of the study is an effort to abstract the correlation between the thermal diffusivity of any material and thermal behavior when exposed to any thermal conditions in the unstable situation. The results of the study indicated a positive correlation between thermal diffusivity and the rate of high temperature [1]. Used two analytical methods for heat convection between the ambient fluid flow and composite conical shell. Finally, to reach the final exact solution of heat conduction equation, an inverse transformation was used. The result of analytical solution was compared with the solution of second order finite different method as well as it tested for solving the industrial cases. The current solution is valid in some industrial cases such as cooling pin fins and aeronautical instruments [2].The thermal diffusivity of bond-coat materials of NiCrAlY type usually used to bond-coat deposition by plasma spraying process was characterized .The influence of analyzed materials' morphology on obtained, by laser- flash method. From results concluded, the morphology of used materials has strong effect of accuracy of obtained data in laser-flash analysis due to differences in microstructure of material. The best thermal data with high accuracy can be obtained mainly by synthesis of specimens in the form of massive alloy[3].The effects of temperature-dependent thermal material properties which took into consideration through Metallic thermal protection system (MTPS) subjected to convection and radiation boundary conditions by a novel approximate analytical method based on orthogonal expansion technique and separation of variables .The proposed method to determine the problem of nonlinear transient heat transfer through a MTPS got a good agreement is presented by comparing with the finite element method (FEM)[4].By using the method of separation of variables combining with Laplace transformation, an analytical solution for two - dimensional modeling of the temperature distribution is found to study repetitive long pulse laser heating of solid materials .The result of analytical solution gave good agreement with the existing finite element method[5].The scaled boundary finite-element method (SBFEM) was used to solve two-dimensional heat conduction problems in steady-state and transient analysis for finding the temperature field in the domain and developed a code in MATLAB to get the numerical simulation of non-homogeneous and anisotropic media. Study results indicated that the SBFEM is an smart pattern in terms of accuracy and its suitability for modeling heat transfer problems with non-homogeneous and anisotropic media[6].A new analytical solution method for transient heat conduction in hollow composite cylinders with an random number of layers is studied and exposed to general boundary conditions. The suggested method is highly efficient in calculation and does not need different derivations for different cylinder shapes[7].Investigations were carried out to study the effect of density on thermal conductivity of bamboo mat board (BMB) and to evaluate the thermal conductivity of BMB by a steady-state guarded hot-plate method .The result showed that the Thermal conductivity of BMB increased with increasing bulk density[8].A problem of transient heat conduction in a one-dimensional three-layer composite slab was studied and solved theoretically .The Eigen function expansion solution is compared with a finite difference numerical solution which given a conjectured partial solution for an n-layer composite slab [9].

The problem of unsteady heat transfer in polar direction was treated by another study using the analytical double-series solution in a cylinder made up of several layers of different materials. The proposed solution to such problems gave acceptable results [10].Heat transfer through metal foams containing open -cell was treated analytically by a study carried out for this purpose. The researcher assumes the pore space to be spherical and subtracted the pore space from a unit cubic of the metal. Thermal conductivity, pressure drop and Nusselt number were calculated. The results were compared with existing experimental measurements and semi empirical models for porosities greater than 80% [11].Two different experimental facilities and a numerical model will be applied to measure the moisture buffering capacity (MBC) of spruce plywood and investigate the effect of initial and boundary conditions and the thickness of the plywood on the measured buffering capacity . From results noticed that MBC depends on the initial conditions and thickness of the plywood as well as the surface film coefficient[12].A steady analytical solution for general linear boundary conditions which suitable for various conditions including combinations of conduction, convection, and radiation both inside and outside the cylinder .To derive an appropriate Fourier transformation, the Sturm–Liouville theorem is used for this problem to get The temperature distribution by applying this transformation to the governing equation .The recursive Thomas algorithm is used for solving a set of equations generated by applying the boundary conditions inside and outside the cylinder, and the continuity of temperature and heat flux at boundaries between adjacent layers[13].An analytical method is presented for the solution of transient temperature filed in multi-dimensional composite circular cylinder .The boundary condition is described as time-dependent temperature change. This method used for solving heat conduction in composite slab in Cartesian coordinates . Close-formed solution is provided and its gave a good agreement with numerical result[14].Thermal conductivity effect on ice friction was studied over a wide range of sliding velocities, and temperatures by insulating slider materials with fiberglass and comparing with different metallic materials .Results of ice friction coefficient appeared that the importance of thermal conductivity decreases with increasing sliding velocity [15].

This review shows the considerable amount of different studies used a numerical, experimental and analytical solution method for transient heat as well as some research study the correlation between the thermal diffusivity and thermal behavior .The effects of temperature - dependent thermal material properties and Thermal conductivity were studied. This study focused on explaining the effect of the length of the sample on the temperatures distribution. The thermal initiation time of the sample was adoption at the response of the material to temperature of hot face as a basis for this study on samples with different thermal properties.

Specification & modeling

To study the transient heat transfer through the samples of different lengths, the temperature distribution through the nodes of the sample is governed by the unsteady one-dimensional heat conduction equation [**16**]:

$$k_n \frac{\partial^2 T}{\partial X^2} = \rho_n c_n \frac{\partial T}{\partial t} \qquad (1)$$

An explicit finite difference numerical solution to obtain the temperature at each node for a single material is given by equation 2 [**17**]:

$$T_i^{j+1} = T_i^j + \frac{\Delta t * K}{\rho * Cp * (\Delta x)^2} * \left(T_{i+1}^j - 2T_i^j + T_{i-1}^j\right) \qquad (2)$$

Where:

T-Temperature

K - Thermal conductivity

ρ -Density

Cp - Specific heat

Δt- Time step

j- Increment time

i- Number of node

Δx - Uniform space between two nodes=1cm

The time step has been tested to assure the convergence and consistency of the numerical scheme.

A numerical study being run by using ANSYS-14(APDL) to predict the thermal initiation time of samples affected by thermal load in transient heat transfer case .Three samples of different length (10,20 & 30)cm with constant height 2.5cm were used, which explained in figure (1). Every sample used three materials (Chromium ,Stainless steel(AISI304) and Cellular glass) with different thermal properties ,as illustrated in table (1) where one face exposed to temperature 100°C and the another exposed to convection at 25°C.Assuming that one dimension heat transfer (x-direction) along the samples ,isolated from above and lower surface and no generation of heat. Another thermal and boundary conditions used in simulation explained in table (2).

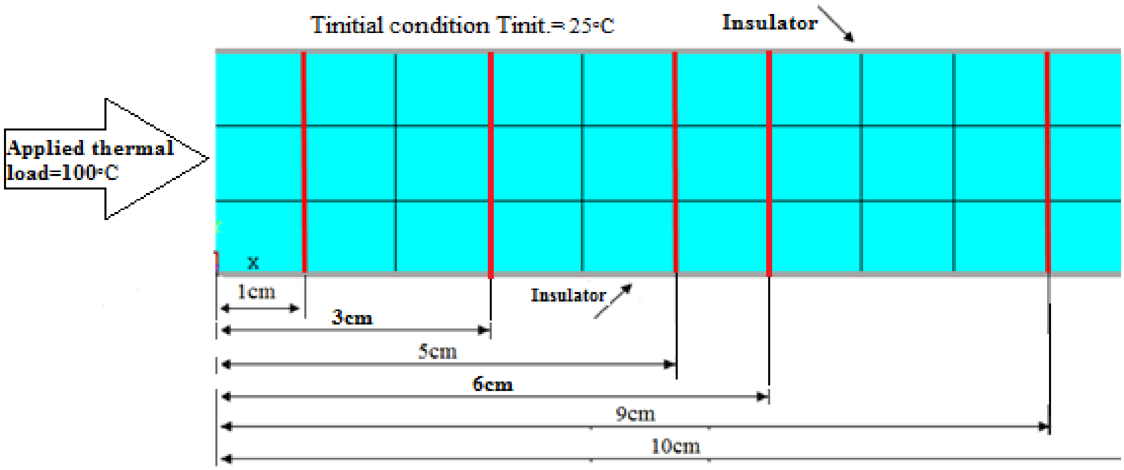


Figure (1-a) L=10cm the selected points for first study at x=(1,5&9)cm and the selected points for second study at x=(1,3,6&9)cm

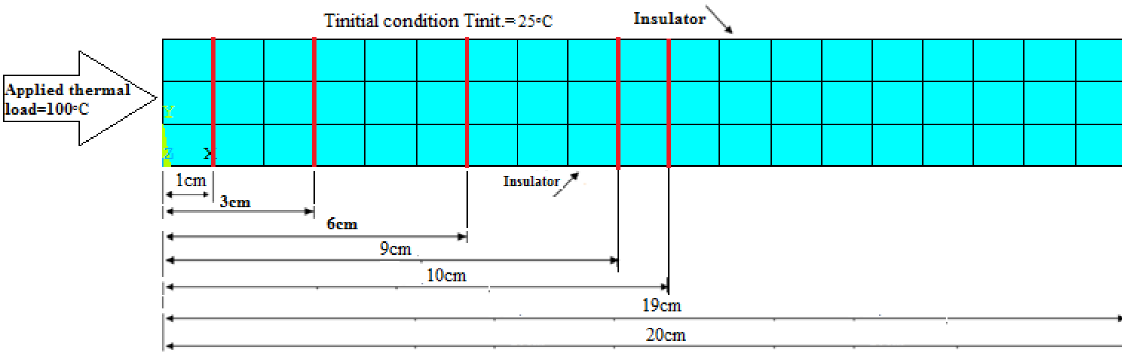


Figure (1-b) L=20cm the selected points for first study at x=(1,10&19)cm and the selected points for second study at x=(1,3,6&9)cm

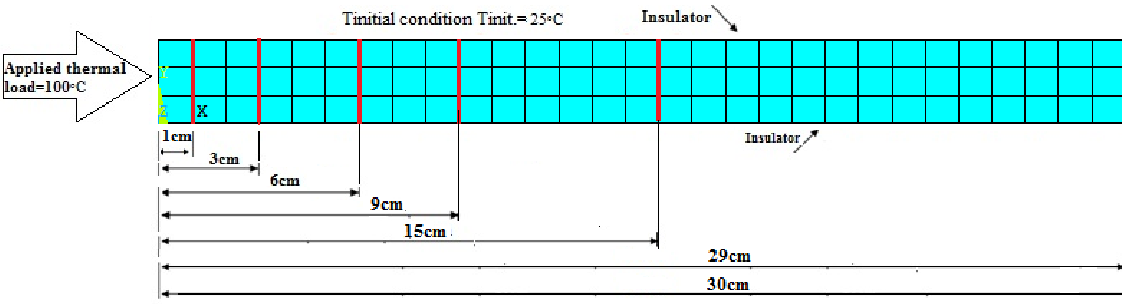


Figure (1-c) L=30cm the selected points for first study at x=(1,15&29)cm and the selected points for second study at x=(1,3,6&9)cm

Figure (1) Specification of samples with the thermal conditions exposed to it

Table (1) Thermal properties of materials used [18&19]

Thermal properties of materials		K (W/m.°C)	ρ (Kg/m^3)	Cp (J/Kg.°C)	(α) (m^2/sec)
Materials	Chromium	93.7	7160	449	α=2.9E-5
	Stainless steel(AISI304)	14.9	7900	477	α=3.95E-6
	Cellular glass	0.055	136	1000	α=4.04E-7

Table (2) Boundary Conditions and Ansys constants

Specimen length (L)	0.10 m			0.20 m			0.30 m		
Specimen width	0.025m								
thermal load in the right side (°C)	Convection at T_∞= 25°C				$h_{conv.}$=10W/m^2.°C				
thermal load in the left side (°C)	100								
Temp. difference between two side (ΔT) (°C)	75								
Initial condition of sample	$T_{initial\ cond.}$ = 25 °C								
Element edge length	0.01m (mesh= medium)								
Preferences for filtering	Thermal								
Type of analysis	Transient								
Materials	Chromium			Stainless steel(AISI304)			Cellular glass		
Specimen length (m)	0.10	0.20	0.30	0.10	0.20	0.30	0.10	0.20	0.30
Time step size (sec)	0.025	0.025	0.025	0.2	0.2	0.2	2	2	2
Number of nodes	10	20	30	10	20	30	10	20	30

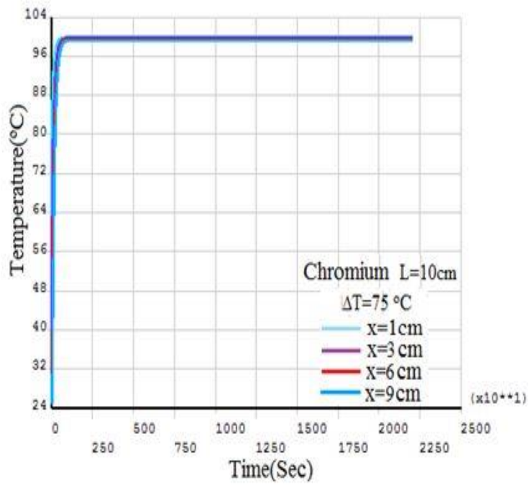
Results and Discussion

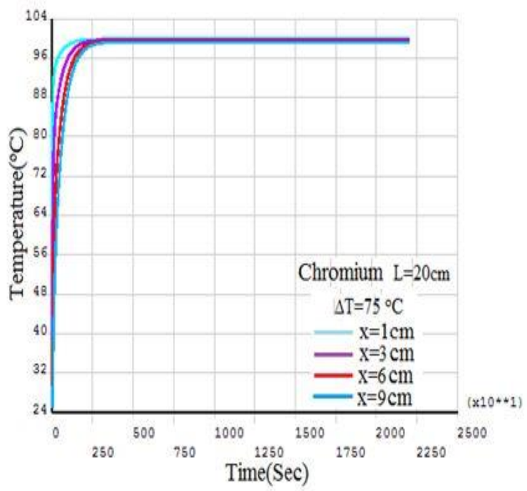
The thermal initiation time of samples was selected from ANSYS program results, when the temperature of samples reached to (26 °C) i.e. rise one centigrade about the initial temperature that characterized the start response of materials to the heat applied.

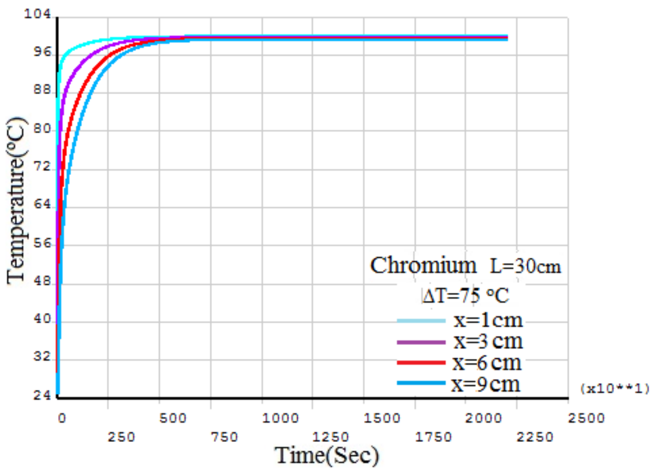
Figure (2) explained the relationship between the time and the temperature for different materials with different lengths from the hot face as follows:-

1-When the heating time is fixed, the points closest to the hot face have a temperature higher than the temperature of the farthest points, and can be expressed in another way, the temperature of closer points to the hot face reach to specific temperature at time less than the time of farthest points, this can be explained by the fact that the heat resistance is reduced due to the low heat transfer distance as approaching the hot face, as well as the rise of the thermal driving force(ΔT)as approaching the hot face. This is what we see clearly in each material with different lengths of samples and the amount of distance from the hot face.

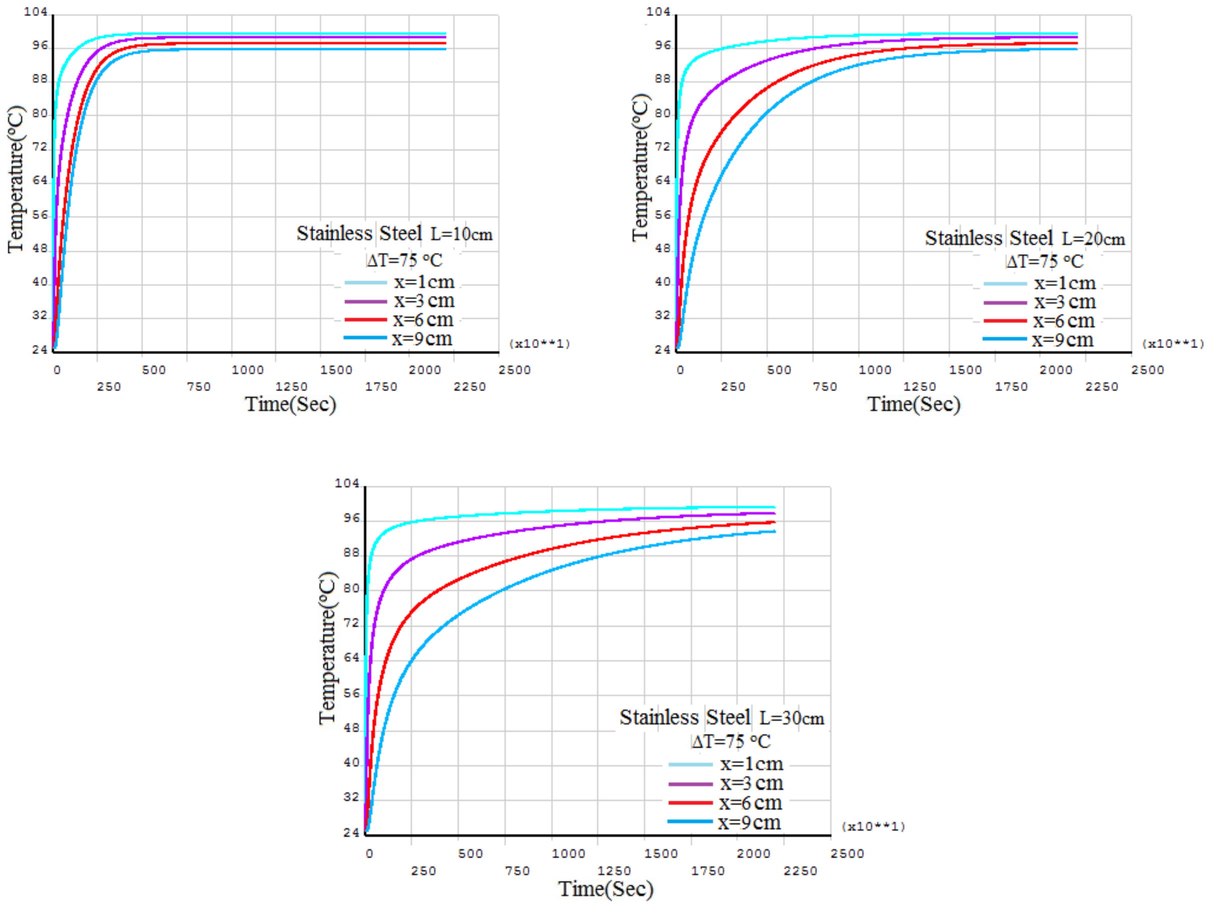
2- When fix the length(L) of sample and distance(x) from hot face, the active variable is the type of material can be expressed by thermal diffusivity(α) ,as example the chromium material with the highest thermal diffusivity, we notice that the time required to reach to specific temperature at any point is lower than in the corresponding points of other materials with low thermal diffusivity.







Figure(2-a) The Ansys Program Results of Chromium



Figure(2-b) The Ansys Program Results of Stainless Steal

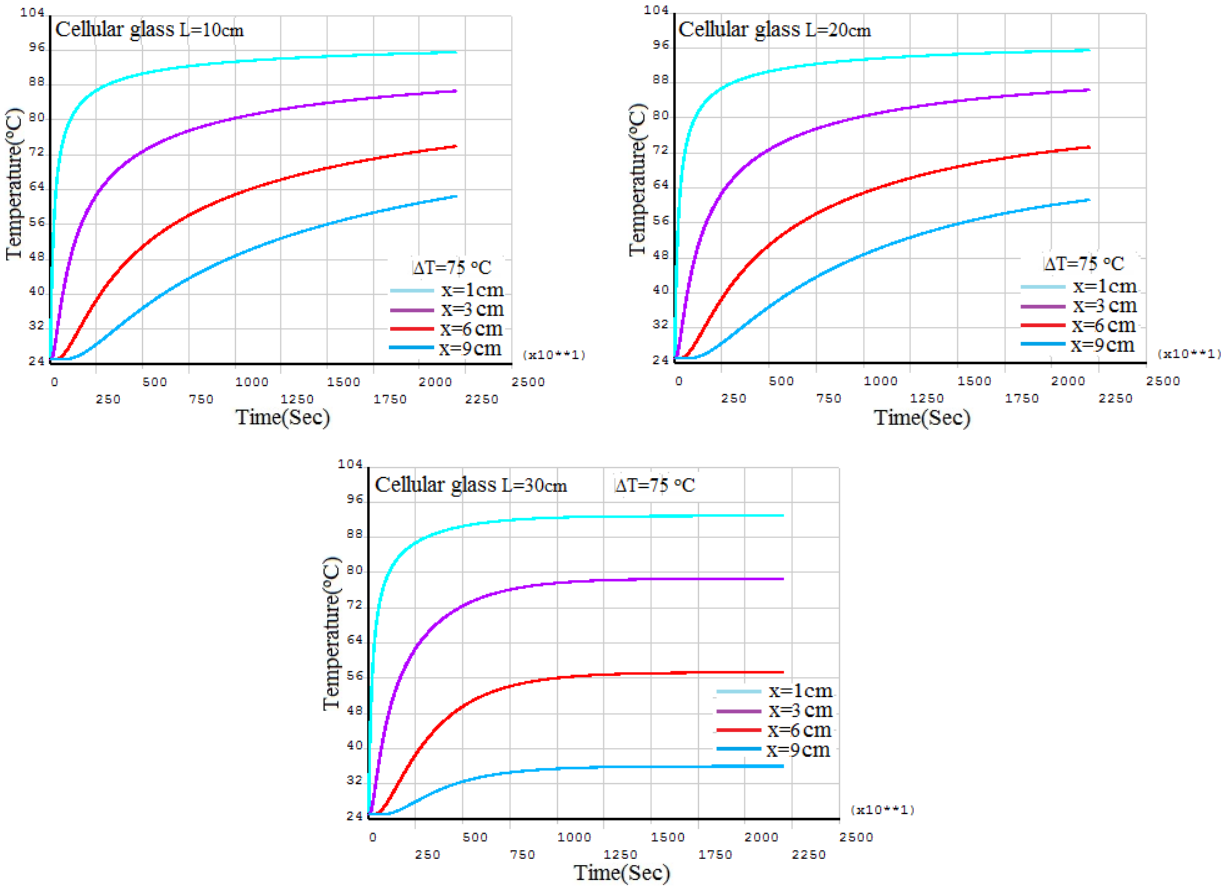
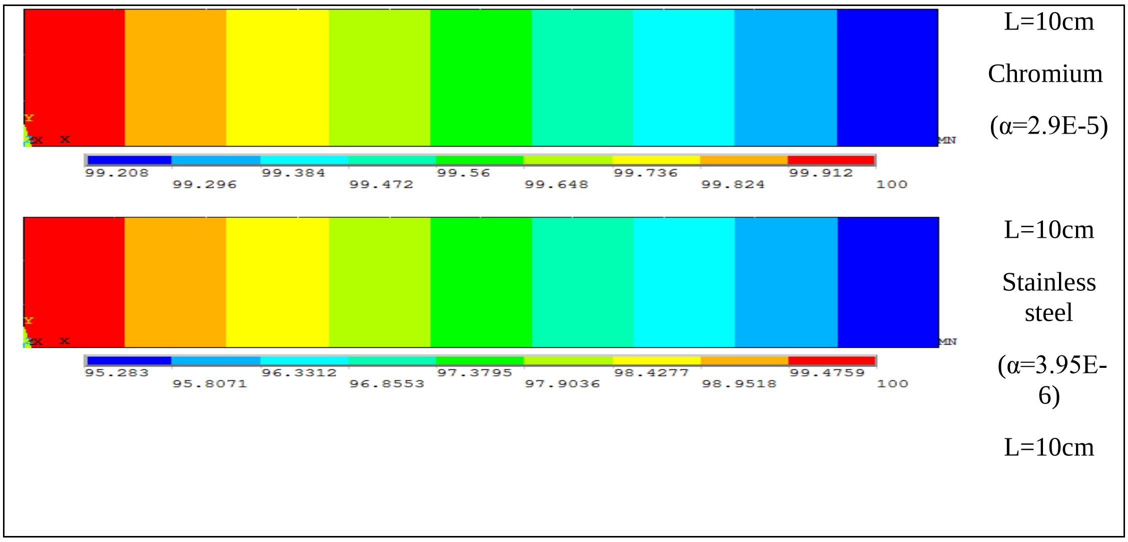


Figure (2-c) the Ansys Program Results of Cellular Glass

Figure (3) confirms the results obtained in Figure (2).The most important characteristic of the results of figure (3), the effect of thermal diffusivity was slightly in the nearest region from the hot face. While the other face, the effect of length of the sample and thermal diffusivity more was clear in the temperature of the sample at those points, which were explained in the images of Ansys Program at the end of the application time =22000 seconds



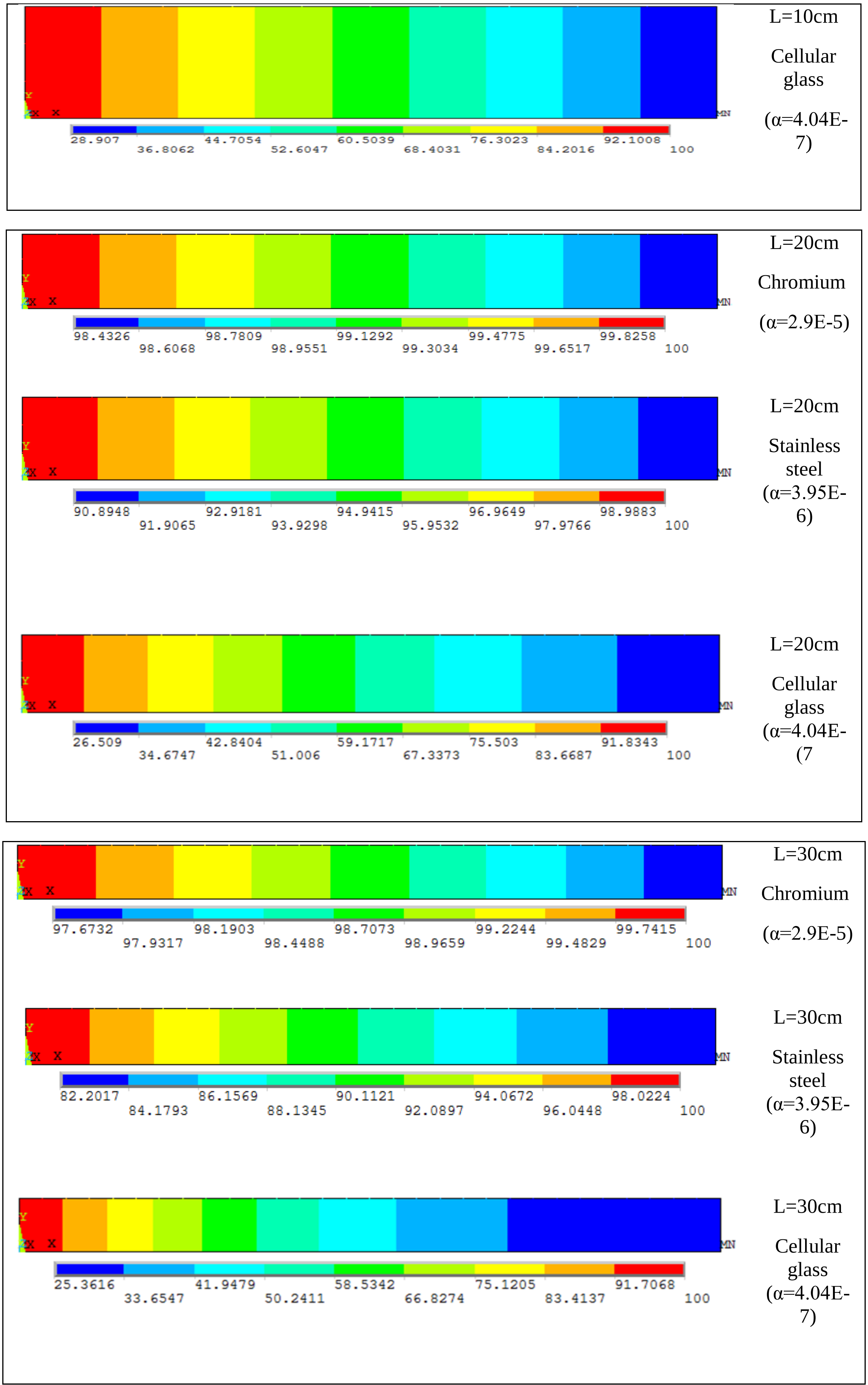


Figure (3) Images from Ansys Program for Temperature Distribution of Samples

Figure (4), shows the relationship between the thermal initiation time of sample and the distance from the hot face with different lengths of the sample, where we notice two basic variables:-

1-The first variable can be observed in Figure 4(a, b&c) at fixed type of material or thermal diffusivity , the thermal initiation time of sample is directly proportional with the length of the sample, and we see this clearly at the points farthest from the hot face of the sample, so that we need more time to thermal initiation time of sample for reaching the temperature 26 ^{o}C.

2-The second variable, which we observe in Figure 4(a, b&c) separately, at constant sample length we note that the value of the thermal diffusivity has a clear effect on the amount of the thermal initiation time of sample and that the effect of diffusion is becoming clearer when move away from the hot face for the low impact of other variables.

Moving away from the hot face means an increase in the value of (x), which represents one of the resistance variables in the heat transfer equation in the stable and unstable state.

The equation(3), shows the relationship between the thermal initiation time of sample and the length of the sample with different distance from the hot face and can be illustrated in the form eq.4. Which represent an exponential relationship contain the variables (c, n) explained in table (3).

Thermal initiation time of sample $(T.I.t)_{(Sec.)} = c_* \, e^{n}$ (3)

Table (3) Constant values of equation (3)

Material type	L=10 cm		L=20 cm		L=30 cm	
	c	n	c	n	c	n
chromium	3.57	2.863	3.48	2.68	3.44	2.62
s. steel	0.37	2.833	0.37	2.62	0.36	2.54
c. glass	0.05	2.84	0.05	2.62	0.05	2.54

The value of the variable (n) ranges between (2.5412 - 2.8630), that represent the amount of distance from the hot face. The variable (c), which is a reflection of the thermal diffusivity, is about (0.05, 0.37 and 3.5).

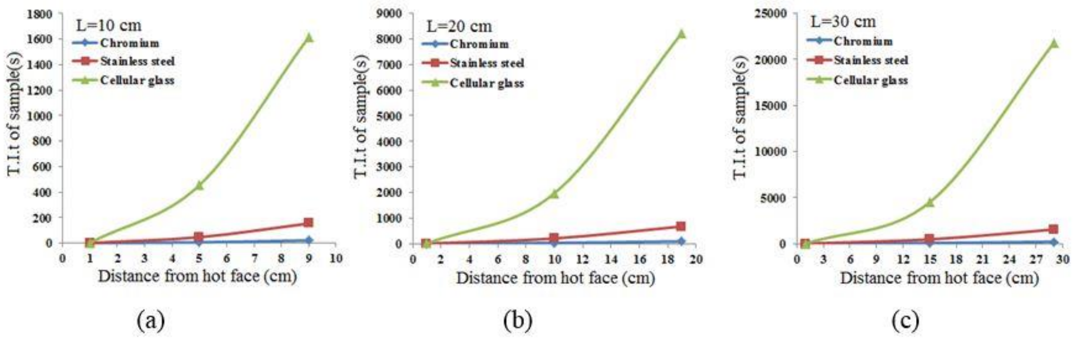
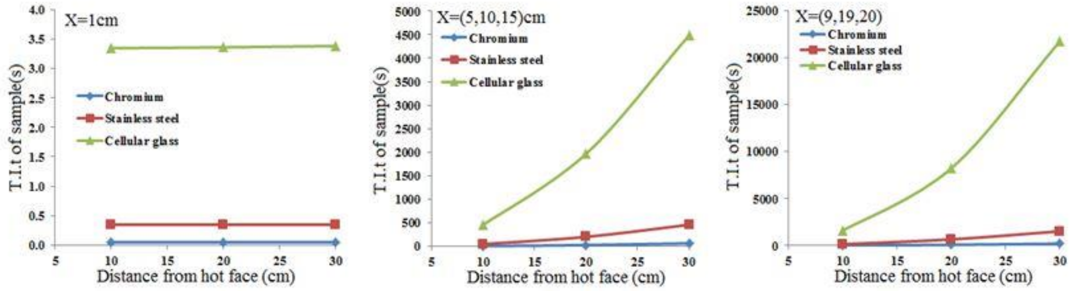


Figure (4) Effect of sample lengths on T.I.t of sample (first study)

Figure (5) which illustrates the effect of the distance(x) from the hot face on the thermal initiation time of sample where:-

1- (x = 1cm), represents the closest point from the hot face, where we note that the time required to be affected this point by heat is very low and reached a maximum of 3.5 seconds for the material with the lowest thermal diffusivity. As for the material with higher thermal diffusivity, it took only 0.1 seconds to response to the heat of the hot face. It is also observed that the length of the sample does not have a clear effect on the thermal initiation time of sample response by heat, where the relationship take the shape of a straight line.

2- At the intermediate points of the samples of different lengths we notice a clear and reciprocal effect of both distance from the hot face and thermal diffusivity. At the L=10 cm sample length, we note that the highest time needed by the midpoint to respond to heat from hot face is just less than 500 seconds for the materials with the low thermal diffusivity and this time is decreased to approaching zero in the materials with the high thermal diffusivity, which leads us to conclude that the distance from the hot face doesn't affect the materials with a very high thermal diffusivity only at the points far from hot face. But the effect of the distance from the hot face increases with the low thermal diffusivity of materials. The relationship between the distance from the hot face and the thermal initiation time of sample took another form, not a straight line, but an exponential relationship in which the effect of thermal diffusivity and distance from the hot face appeared clearly. At the endpoints of the samples we observe the effect of thermal diffusivity and distance from the hot face more clearly on the thermal initiation time of sample.



Figure(5) Effect of distance from the hot face on T.I.t of sample(first study)

From figure (6) the relationship between the thermal diffusivity and thermal initiation time of samples get an inverse relation where the curves take an exponential inverse relationship due to an which explained in equation (4).

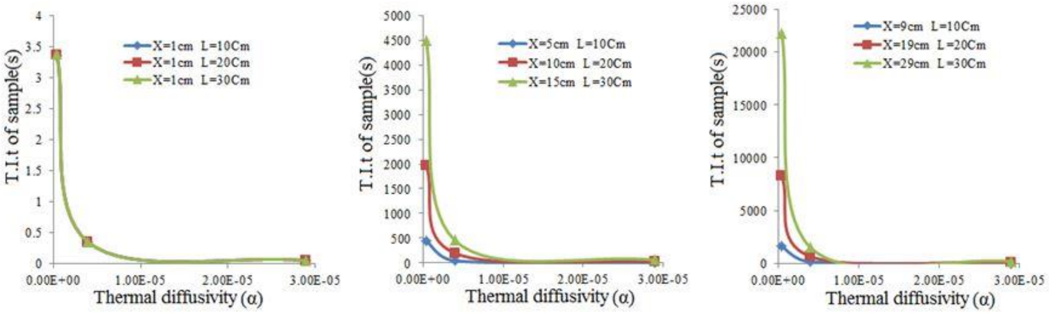
$$T.I.t_{(Sec.)} = a_* (\alpha)^{-b} \qquad (4)$$

Table (4) Constant values of equation (4)

Distance from the hot face	a	b	R^2
X=1cm	1E10-6	1.002	1
X=(5,10&15)cm	0.00002 - 0.0018	1.001	1
X=(9,19&29)cm	0.0005- 0.0022	1.018- 1.091	0.9999

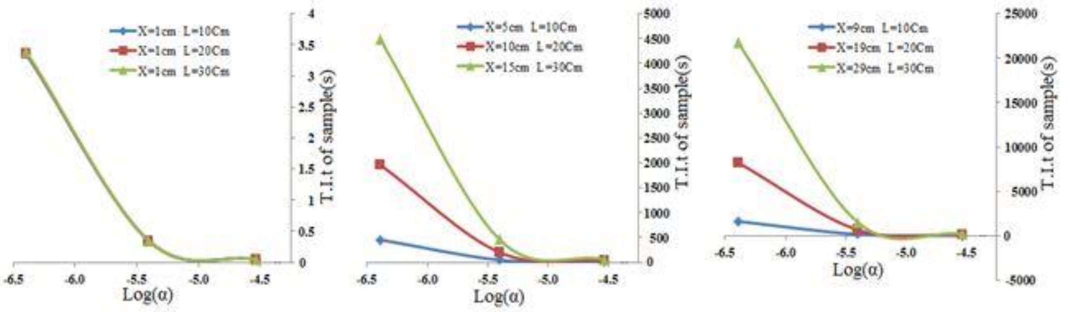
The thermal initiation time of samples decreases as thermal diffusivity increased at

- Constant length of sample.
- Constant the distance from the hot face.



Figure(6) The relationship between Thermal diffusivity(α) and T.I.t of sample(first study)

The same results can be obtained but more clearly when plotting the relationship between the thermal initiation time of samples and the logarithm of thermal diffusivity as shown in Figure (7).

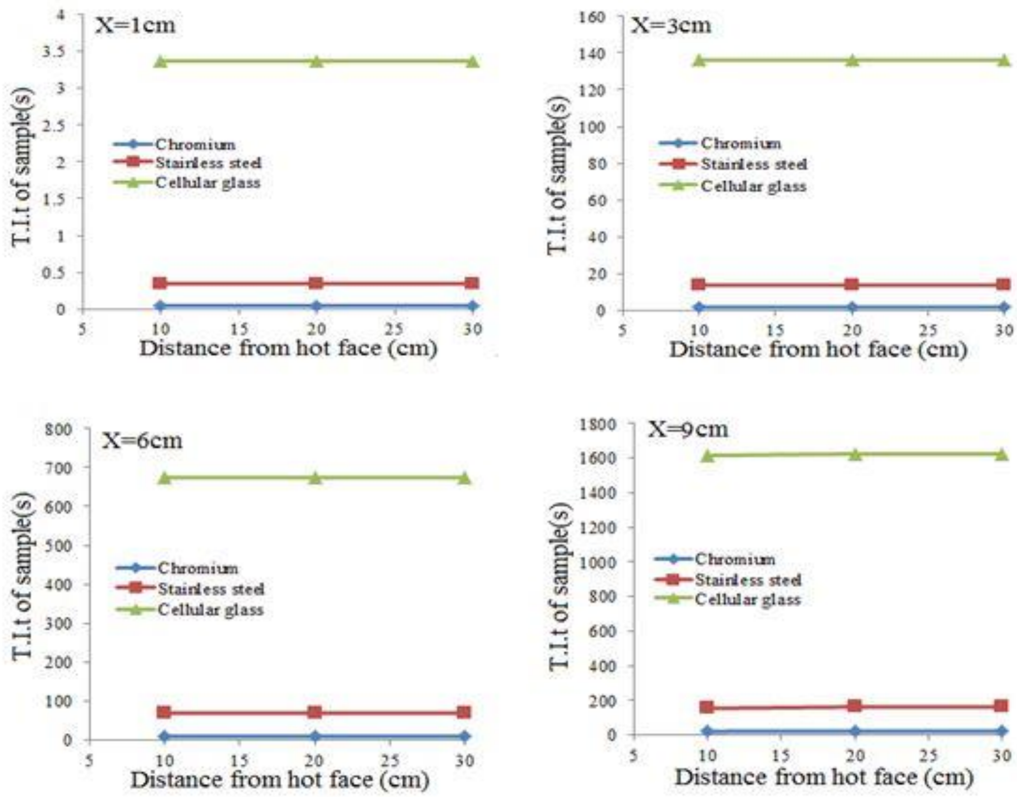


Figure(7) The relationship between log.(α) and T.I.t of sample

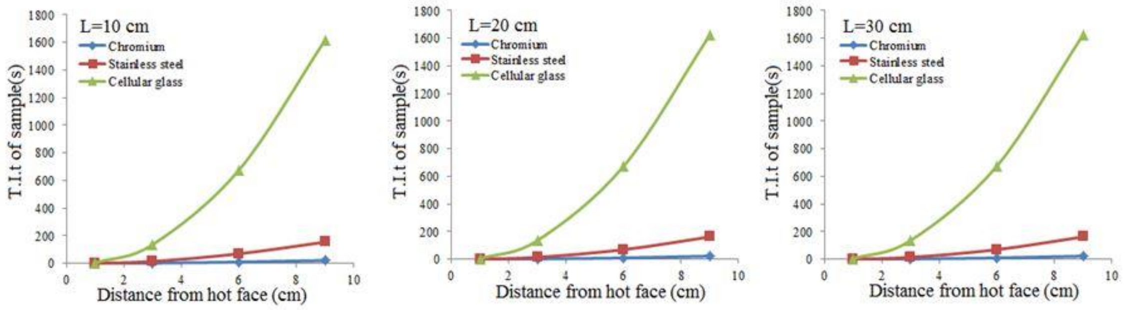
Figure (8) explains the relationship between the thermal initiation times of samples with the distance from the hot face.

At (x = 1cm), when the thermal diffusivity is fixed also , we did not observe any effect of the length of the samples on the thermal initiation time at those points where the relationship is a straight line parallel to the x- axis. As well as the effect of thermal diffusivity can be observed clearly on the thermal initiation time of samples. From the other figures at the points farthest at x= (3, 6 &9) cm, the same results are observed that may be seen at x = 1 cm indicating that there is no effect of the length of the samples to the equivalent points on the thermal initiation time.

Figure (9) Confirms the results obtained from Figure (8).



Figure(8) Effect of equivalent distance(x) on T.I.t of sample(second study)



Figure(9) The effect of samples length on T.I.t of sample(second study)

Conclusions

1- The relationship between the thermal initiation time of sample and the distance from the hot face is a positive when the thermal diffusivity is constant.
2- The relationship between the thermal initiation time of sample and the thermal diffusivity is inverse relation when the distance from the hot face is constant.
3- The length of the sample has no effect on the thermal initiation time of sample at the equivalent points located on a fixed distance from the hot face.

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دراسة عددية لتقييم زمن البدء الحراري للعينة المتأثرة بواسطة الحمل الحراري المسلط

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الخلاصة

تم دراسة زمن بداية تأثر النماذج بالحمل الحراري المسلط على طرفي النماذج عدديا باستخدام برنامج ANSYS-14خلال انتقال الحرارة غير المستقر. تم اختيار ثلاثة نماذج ذات اطوال مختلفة (10، 20 و30) سم وبارتفاع ثابت 2,5 سم وتم اختيار ثلاثة مواد ذات خواص حرارية مختلفة (مادة ذات انتشارية حرارية (α) عالية ومادة متوسطة الانتشارية ومادة ذات انتشارية حرارية منخفظة) وطبقت على جميع النماذج الثلاثة. عرضت النماذج الثلاث الى حمل حراري ثابت 100 درجة مئوي على أحد الاوجه وعرض الوجه الاخر الى حمل حراري 25 درجة مئوي. وتم اعتماد زمن بداية تاثر النماذج عند وصول درجة حراراة النقاط التي تم اختيارها الى 26 درجة مئوي والتي هي اعلى بدرجة مئوية واحدة عن الظروف الابتدائية والذي يمكن اعتماده كمقياس للموصلية والتي تمثل استجابة المادة للحرارة المسلطة عليها. ان الهدف من هذه الدراسة هو لمعرفة زمن بداية تأثر النماذج ذات الاطوال المختلفة ولمواد ذات خواص حرارية مختلفة عند مجموعة من النقاط على طول النماذج عند البداية والمنتصف والنهاية كدراسة اولى. اما الدراسة الثانية فقد ركزت على اعتماد بعد ثابت عن الوجه الساخن لجميع اطوال العينات عند مجموعة من النقاط المتناظرة (1، 3، 6 و9) سم. بينت نتائج الدراسة الاولى ان زمن بداية تاثرالنماذج يزداد مع زيادة البعد عن الوجه الساخن واعطيت العلاقة بينهما علاقة طردية اسية عند ثبوت الانتشارية الحرارية، كما بينت الدراسة ان العلاقة بين زمن بداية تاثر النماذج والانتشارية الحرارية علاقة عكسية اسية عند ثبوت البعد عن الوجه الساخن حيث كان زمن تاثر كل من مادة الكروم ذات الانتشارية الاعلى عند 26 درجة مئوي يتراوح بين (0.0465 – 207.28) ثانية ومادة الزجاج الخلوي ذات الانتشارية الواطئة يتراوح بين (3.348 – 21762) ثانية لاقرب وابعد نقطة عن الوجه الساخن. وأظهرت الدراسة الثانية أن طول العينة ليس له تأثيرعلى زمن بداية تاثر العينة بالحرارة عند نقاط متناظرة تقع على مسافة ثابتة من الوجه الساخن.

الكلمات الداله: الانتشارية الحرارية (α)، انتقال الحرارة الغير مستقرة، زمن بداية تاثرالعينة، الخواص الحرارية، الطرق العددية لانتقال الحرارة.