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Heat Transfer Modeling in Multi-Layer Cookware using Finite Element Method

Mohammad Reza Sedighi, Behnam Nilforooshan Dardashti

***Abstract*—**The high temperature degree and uniform Temperature Distribution (TD) on surface of cookware which contact with food are effective factors for improving cookware application. Additionally, the ability of pan material in retaining the heat and non-reactivity with foods are other significant properties. It is difficult for single material to meet a wide variety of demands such as superior thermal and chemical properties. Multi-Layer Plate (MLP) makes more regular TD. In this study the main objectives are to find the best structure (single or multi-layer) and materials to provide maximum temperature degree and uniform TD up side surface of pan. And also heat retaining of used metals with goal of improving the thermal quality of pan to economize the energy. To achieve this aim were employed Finite Element Method (FEM) for analyzing transient thermal behavior of applied materials. The analysis has been extended for different metals, we achieved the best temperature profile and heat retaining in Copper/ Stainless Steel MLP.

***Keywords*—**Cookware, Energy optimization, Heat retaining, Laminated plate, Temperature distribution

I. INTRODUCTION

WE can meet the wide variety of demands such as superior mechanical and thermal properties by using multi materials together[1], [2]. Choosing of multi-layer structure and materials of layers can be effective on improving TD and heat storing. It can optimize the energy consumption. The energy obtains mainly from burning gas and electrical resistivity. The heat is not uniformly spread over the pan in both methods. Using MLP causes regular TD on the top while bottom heated irregularly [3], [4], [11].

Kitchens are one of the places where deals with this phenomenon daily in cookware application. This leads us to two considerations: thermal diffusivity and reactivity. Thermal diffusivity determines how fast the pan will heat up. We do not have to concern ourselves with the thermal properties of materials only, but we need to make sure that the materials we use in our cookware do not harm us or adversely affects the taste of our food [24]. For this reason, in addition to the high thermal diffusivity, we would also like non-reactive materials. copper and aluminum have high thermal diffusivity but both of them reacts readily to foods (copper and aluminum can threat healthy [21], [22]) while some materials like stainless steel, the least reactive of all popular materials used in cookware, also has the low thermal diffusivity. By combining the non-reactive surface of some materials such as stainless steel with the thermal properties of copper or aluminum, achieves the best results [5]. Consequently, the pan should be constructed of conductive metal in bottom layer such as copper and aluminum that are great conductor of heat and non-reactive metal therefore safe to use with any food product in upside of pan which is exposed to food [6].

In the other hand cast iron has a large heat capacity as compared with the other materials. When the cooking task requires the ability to maintain consistent and ample amount of heat, cast iron is desirable. Even after you remove your cast iron from the heat source, the heavy metal of pan keeps the food warm. Also It is easy to use and care for wide range of cooking. These attributes make it such a good cookware [7].
We used Grey Cast Iron (GCI) because it has greater thermal properties [8], [9].GCI's high thermal conductivity and are often exploited to make cast iron cookware.

Reference [10] has optimized thickness and material of the bottom layer containing different alloys of aluminum or copper. It showed that the optimum thickness is 8 (mm) for copper and 6–7 (mm) for aluminum. As demonstrated in [12] for the stainless steel and titanium in second layer, the TD are almost equivalently.

In this paper, at first we represented advantage of using MLP to provide the more uniform TD than single layer by comparison of the Cu and Cu/SSt pan. We used multi-layer pan by bonding highly conductivity and non-reactive materials consist of Al/Cr-Ni, Al/SSt, Cu/Cr-Ni, Cu/SSt and GCI as single layer pan. We found the best metals in the mentioned metals to provide the maximum temperature degree and uniform TD on food preparation surface of pan and finally best heat retaining for constructing pan product with optimum performance.

In this study, we have employed FEM to calculate the temperature profile all over the pan and we showed how much wall of pan affects in heat transfer causes highly temperature gradients.

TABLE I
SYMBOLS AND THICKNESSES

Metals	Symbols	Thicknesses
Copper	Cu	8 (mm)
Aluminum	Al	6.5 (mm)
Stainless Steel	SSt	2 (mm)
Chromium-Nickel	Cr-Ni	2 (mm)
Grey Cast Iron (single layer)	GCI	10 (mm)

II. MODELING

A. Boundary Condition and Model geometry

As we want to model irregularly heating we constrained annular part of the circular surface of bottom side pan, which illustrated in Fig. 1 as Δr, by constant temperature about 773

Young Researchers Club, Islamic Azad University Bueenzahra Branch, Bueenzahra, Qazvin, Iran (phone: (+98 935)7816710; e-mail: Se_Mohamad67@yahoo.com).
Mechanics Department, Islamic Azad University Bueenzahra Branch, Bueenzahra, Qazvin, Iran (phone: (+98 935) 4555452; e-mail: B.Nilforooshan@gmail.com).

(K). There is a geometrical symmetry so the system can be modeled by rectangle plane with length of the pan radius and a thin and long rectangle as wall of pan. Because of the symmetry, the temperature gradients at the centre of plate along the y-axis have zero value. Hence there is no heat flux at the centre of plate along the y-axis. Side of pan has convection heat transfer with air in ambient temperature. We have taken thickness of layers according to Table I. Δr is 2 (cm). The ambient temperature and the coefficient of heat transfer have been assumed as 293 (K) and 17 (W/ (m².K)), respectively. In addition, it is also assumed that the pan is filled up by water with boiling temperature, and the coefficient of heat transfer between the pan and the water is 50 (W/ (m².k)).

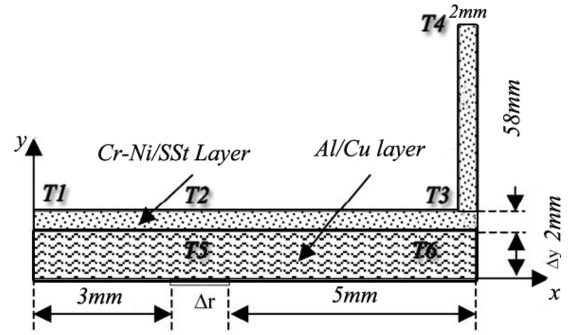

Fig. 1, 2D bi-layer model in numerical analysis and positions of different selected nodes, named T1-T6

B. Meshing

The model was meshed with PlANE55.this element can be used as a plane element or as an axis-symmetric ring element with a 2-D thermal conduction capability and it capable to modeling the axis-symmetric geometry. The element has four nodes with a single degree of freedom, temperature, at each node. The element is applicable to a 2D, steady-state or transient thermal analysis.

III. FINITE ELEMENT METHOD

In the finite element method, a given computational domain is subdivided as a collection of a number of finite elements, subdomains of variable size and shape, which are interconnected in a discrete number of nodes. The solution of the partial differential equation is approximated in each element by a low-order polynomial in such a way that it is defied uniquely in terms of the solution at the nodes. The global solution can then be written as series of low-order piecewise polynomials with the coefficients of series equal to the approximate solution at the nodes [13].

With the advent of digital computers, discrete problems can generally be solved readily even if the number of elements is very large. As the capacity of all computers is finite, continuous problems can only be solved exactly by mathematical manipulation. The available mathematical techniques for exact solutions usually limit the possibilities to over-simplified situations [14].

Various discretization methods have been used in the past for numerical solution of heat conduction problems. It must be emphasized that – particularly in the case of nonlinear heat transfer problems – the numerical solution must always be validated [13].

Use to solve the transient heat conduction process is governed by:

$$\frac{\partial}{\partial x}(k_x\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial T}{\partial y})=\rho c(\frac{\partial T}{\partial t}) \tag{1}$$

The finite element method can be applied as:

$$KT+C\dot{T}=P \tag{2}$$

The ρ denotes the material density, *c* the specific heat of material at constant pressure, and C the damping matrix of the thermal system. In the finite element analysis, the numerical integration is carried out through *N* time steps. Between two adjacent time steps, the *j*th and (j-1)th, we can have the following approximation:

j= (1, 2, …, N)

$$T=(1-\lambda)T_j+\lambda T_{j-1}$$

$$\frac{dT}{dt}=\frac{T_j-T_{j-1}}{\Delta t} \tag{3}$$

The λ is the relaxation parameter. The finite element equation (2) becomes:

$$\left[(1-\lambda)K+\frac{C}{\Delta x}\right]T_j=\left[\frac{C}{\Delta x}-\lambda K\right]T_{j-1}+F \tag{4}$$

By solving (4), temperature fields T at different time steps are found [15].

There are many papers, used FEM to calculate thermal buckling of laminated plate subjected to uniform or non-uniform temperature [16]-[20]. As stated earlier we employed finite element analysis of heat transfer to calculate the TD in laminated plate which heated non-uniformly.

IV. FINITE ELEMENT ANALYSIS

We analyzed the model by using different materials in transient behavior to reach steady state. In this part we want to analyze TD and temperature degree on top surface of pan. After that, in second step we changed the boundary conditions and again we analyzed transient behavior to reach equilibrium point for analyzing the heat retaining of used metals. We employed finite element method with ANSYS program to find both better structure and materials that provides more uniform TD and heat retaining in the pan production. The time step is determined automatically. The time step size is increased or decreased during solution, depending on how the model responds. It gets shorter for any significant amount of deformation to occur.

TABLE I [8], [23]
DENSITY AND THERMAL PROPERTIES OF METALS

Symbol	Density (kg/m^3)	K (W/m.K) C (J/Kg.K)			
		T=200K	T=400K	T=600K	T=800K
Cu	8933	413 356	393 397	379 417	366 433
Al	2700	237 798	240 949	231 1033	218 1146
Cr-Ni	8400	12 420	14 480	16 525	21 545
SSt	8055	15.1 480	17.3 512	20 559	22.8 585
		293°K	473°K	573°K	773°K
GCI	7340	55 490	41	37 585	31 675

V. RESULTS

A. TD of single layer in comparison with bi-layer structure

It's obviously when the model reached to steady state, the maximum temperature on upside surface of Cu pan is higher than Cu/SSt, its771.618 (K) and 769.66 (K) respectively. But the difference between maximum and minimum temperature on food preparation surface of Cu and Cu/SSt pan in steady state is 32 and 25 degrees respectively. It showed that TD in Cu/SSt multi-layer pan is more uniform than Cu single layer pan. In Fig. 2, 3 are illustrated the differences between maximum and minimum temperature during analysis time. It is observed that this difference for Cu in beginning of analysis is about 80 degrees greater than Cu/SSt and it is decreased to 7 degrees in steady state. Fig. 2, 3 represent that MLP provides more uniform TD upside surface of multi-layer pan than single layer.

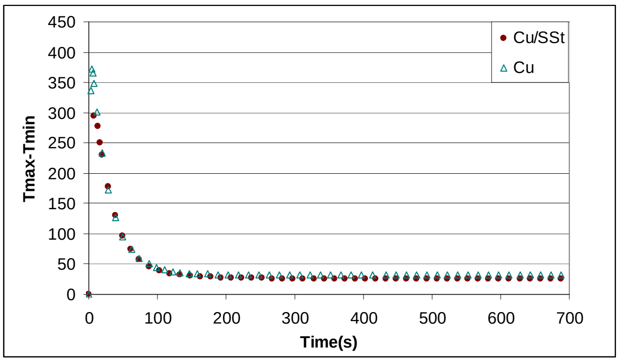

Fig. 2 Time variation of differences between maximum and minimum temperature on food preparation surface of Cu and Cu/SSt pan

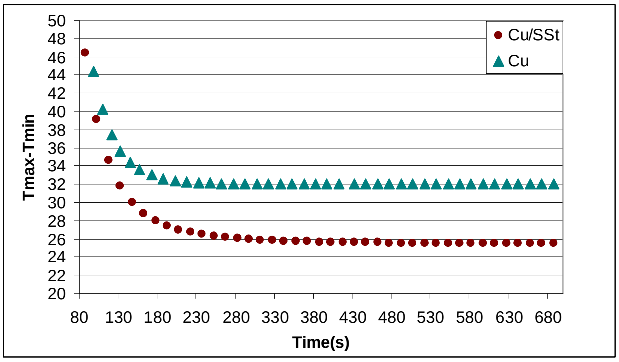

Fig. 3 Time variation of differences between maximum and minimum temperature on food preparation surface of Cu and Cu/SSt pan

B. Results of TD in different materials

We used combinations of metals in bi-layer structure consist of Cu/SSt, Cu/Cr-Ni, Al/SSt and Al/Cr-Ni. It is predictable that minimum temperature observed at edge of wall. There is highly temperature gradient so it represented high convection heat transfer side of pan. We have the regular and uniform TD in all MLP as compared with single layer and between these MLP, Cu/SSt combination has maximum temperature profile. The minimum temperature in Cu/SSt is greater than minimum temperature of other combinations and its about451.1 (K) illustrated in Fig. 4.

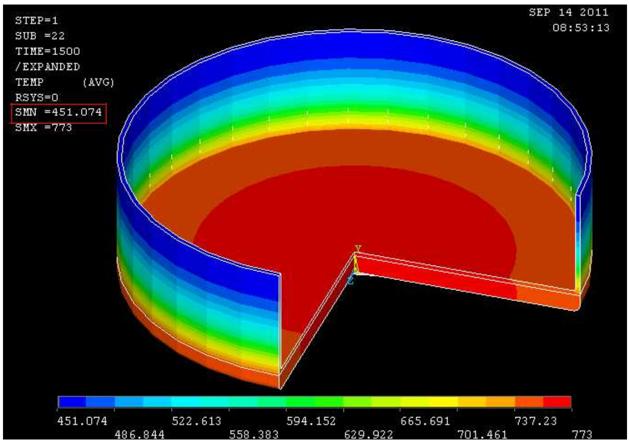

Fig. 4, 3D-TD of Cu/SSt bi-layer pan at steady state

Fig. 4 illustrates uniform TD upside surface of Cu/SSt pan because we used high conductive metal in bottom layer to transfer heat quickly but in second layer is used a metal that has too low conductivity to transfer heat quickly so the heat has opportunity to spread over first layer which has high conductive metal. Therefore uniform heat flux from this layer is transferred to second layer relatively. In another word it is like that we used a heat source which spread the heat uniformly over the plate.

Different positions of pan at different time after analysis start, reach to steady state so we chose 4node at various point of pan called T1-T4 that illustrated in Fig.1.

As stated earlier we solved this model with another combination as follow. The minimum temperature of Al/SSt, Cu/Cr-Ni, and Al/Cr-Ni after 1500 second reached to steady state are 447.266 (K), 431.441(K), and 428.232 (K) respectively. In all them we observed regular TD on surface which contact with foods while heated irregularly because of using bi-layer plate. Transient thermal behavior of all bi-layer pans to reach steady state illustrated in Fig. 5-8

You see some differences among Fig. 5, 8. The T2 node in combination consists of Al after 30 second is higher than Cu combination. It is predictable because thickness of Al is lower than Cu thickness so the heat flux reaches to T2 point sooner.

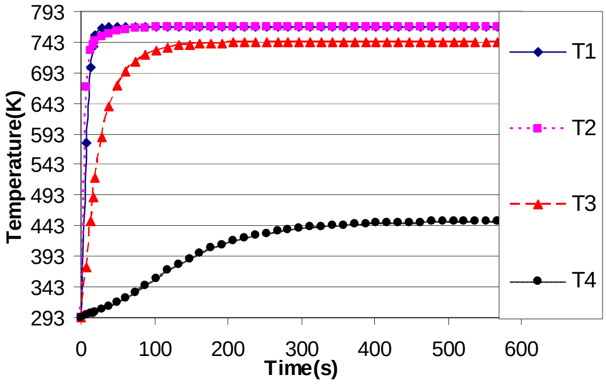

Fig. 5 Time variation of temperature in Cu/SSt pan

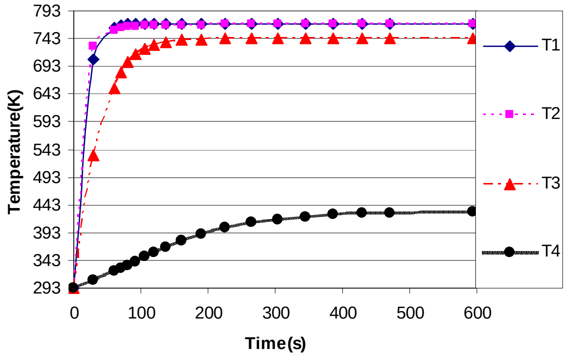

Fig. 6 Time variation of temperature in Cu/Cr-Ni pan

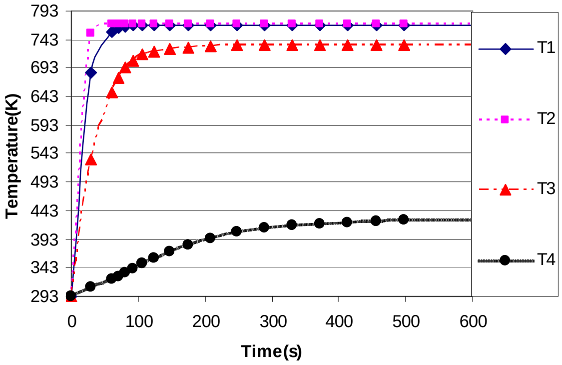

Fig. 7 Time variation of temperature in Al/Cr-Ni pan

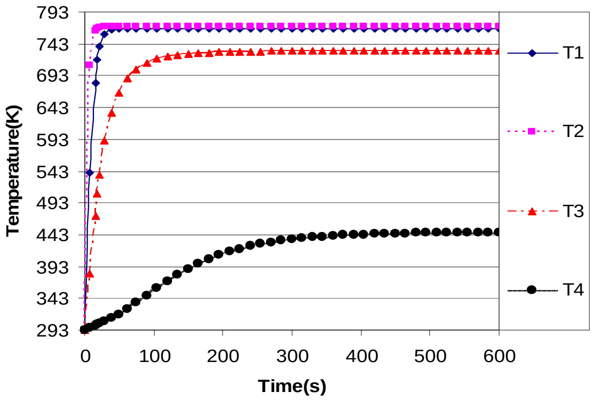

Fig. 8 Time variation of temperature in Al/SSt pan

We compared transient response of T4node with all combinations. Temperature variations of T4 node in all combinations during first 100 seconds are same approximately. After this time we observed some differences between bi-layer pan containing SSt and bi-layer pan including Cr-Ni layer obviously. Insofar as after 500 seconds it is apparent about 17 degree differences between them as shown in Fig. 9.

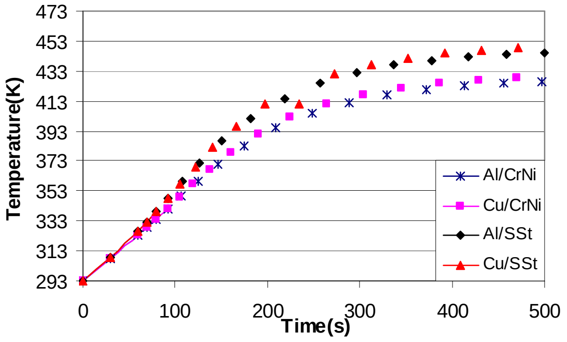

Fig. 9 Temperature variation comparison of T4 node for all combination bi-layer pans

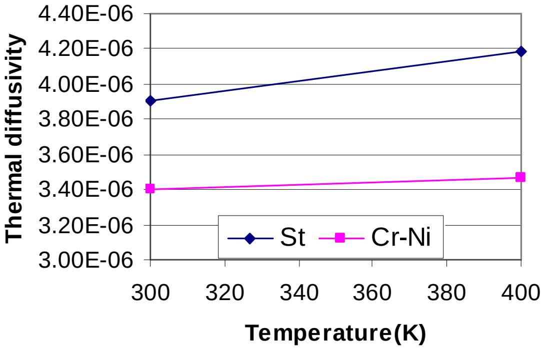

Fig. 10 Temperature variation of Thermal diffusivity in SSt and Cr-Ni

This difference is originated from SSt and Cr-Ni properties. Thermal diffusivity of SSt is greater than Cr-Ni and by increasing temperature, differences of thermal diffusivity of SSt and Cr-Ni became greater that illustrated in Fig 10.

Cast iron has played role in cookware.GCI has high heat capacity and density so we compared the metals that are analyzed earlier with GCI. We have done the above processes for single layer GCI.

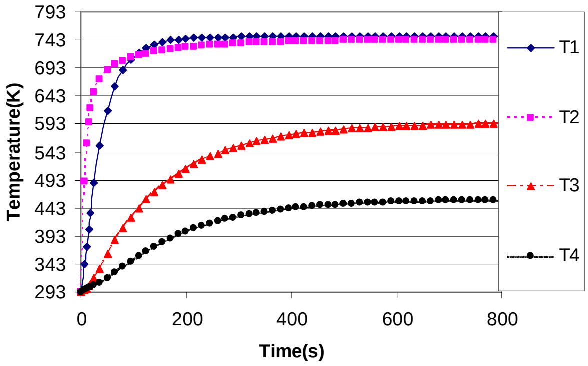

Fig. 11 Time variation of temperature in GCI pan

In GCI pan, the difference between maximum and minimum temperature in steady state is a smaller amount than another analyzed cases because it is single layer and all over the model has same properties whereas in combinations bottom layer has high conductivity but top layer has low thermal properties and it is caused, the difference between maximum and minimum temperature in MLP became greater. In the other hand, the temperature of upside surface of GCI pan is lower than other analyzed cases and it isn't desirable in cooking as cookware application.

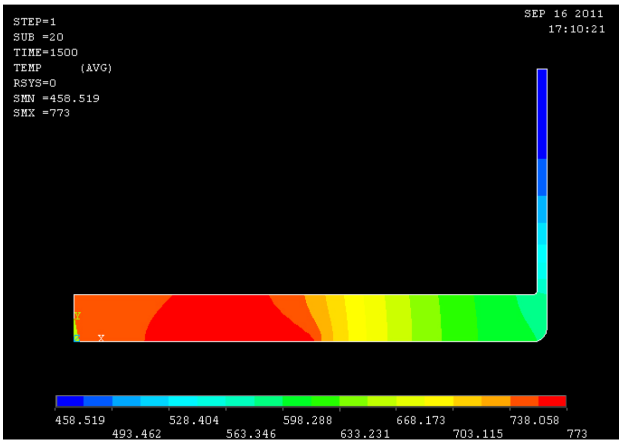

Fig. 12 TD of GCI single layer pan at steady state

By comparison transient behavior of GCI and combinations, we observed after about 90 second is provided uniform TD top surface of the multi-layer pan relatively whereas GCI cannot provide the uniform or even regular TD during the analysis time to reach steady state. Fig. 12 illustrated that TD in single layer is not uniform as stated earlier clearly, especially in low conductivity metals such as GCI. By comparison of T1, T2 ,T3 nodes of model in all materials, Fig. 5-8, 11, it is showed that which one can provide more uniform TD. As a result Cu/SSt combination provided most uniform TD and highest temperature degree on surface which contact with foods between studied cases. After it the combinations consist of Al and finally GCI pan.

C. Results of Heat Retaining

After that the model reached to steady state we changed the boundary conditions of pan to analyzing the heat retaining of the model. Hence we modeled the heated pan to transfer the heat just with air at ambient temperature for cooling. The results of this analysis are illustrated in Fig. 13-17 for all used metals. We compared the T5 node of model with all applied metals as shown in Fig. 18. It represents the heat storing differences of studied cases clearly. It shows that the pans consist of Cu can retain the heat better than others even GCI. But the cookware containing Al cannot retain the heat well in compare with Cu and GCI. The GCI because of the high specific heat and density and low conduction coefficient have low thermal response so it has good heat retaining. You see that temperature of T4 node first increase and then it decrease because T4 node has minimum temperature in compared with all over the pan so there is a heat flux from high to low temperature degree. In the other hand conduction coefficient of metals is very greater than convection coefficient of air.

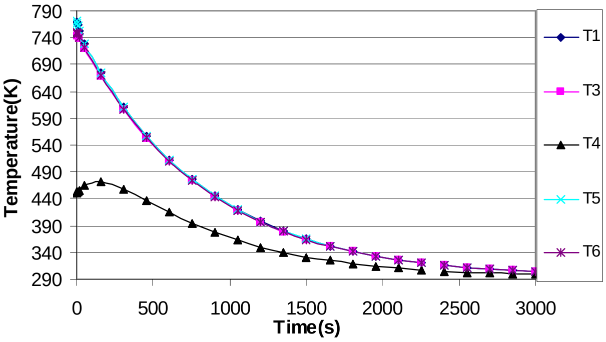

Fig. 13 Time variations of temperature for cooling the Cu/SSt pan

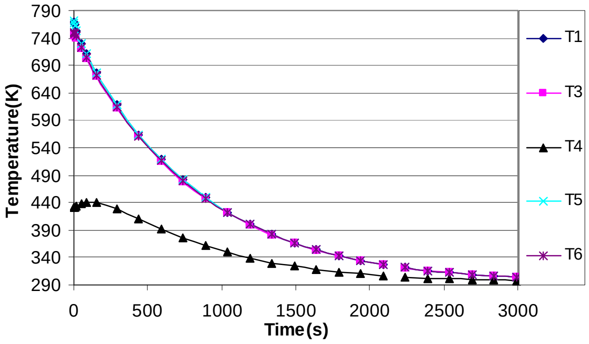

Fig. 14 Time variations of temperature for cooling the Cu/Cr-Ni pan

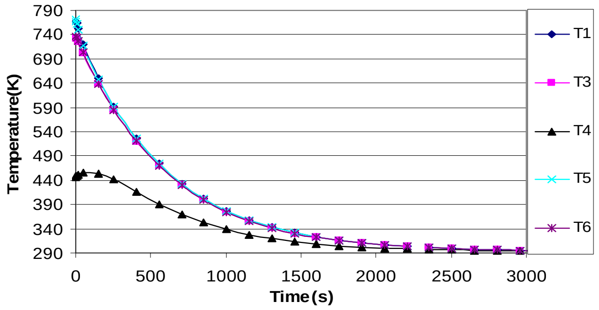

Fig. 15 Time variations of temperature for cooling the Al/SSt pan

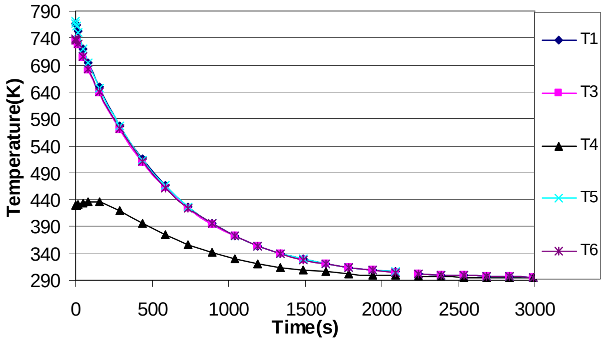

Fig. 16 Time variations of temperature for cooling the Al/Cr-Ni pan

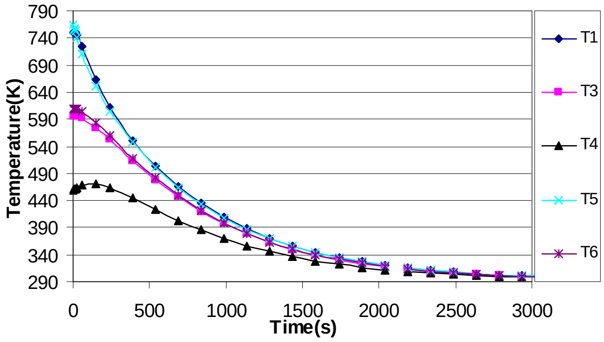

Fig. 17 Time variations of temperature for cooling the GCI pan

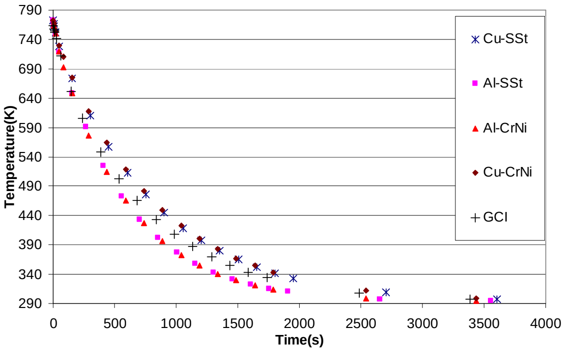

Fig. 18 Temperature variation comparison of T5 node for all metals in cooling step

VI. CONCLUSION

This paper describes the numerical, finite element method, analysis of transient thermal behaviors of the single metal and MLP heated irregularly to improving the thermal behavior of cookware. First we showed that multi-layer structure provides more uniform TD upside surface of pan. By combining metals of higher thermal conductivity with metals of lesser conductivity but higher inertness achieved the best in cooking therefore the thermal quality advantage of laminated plate in the cookware deduced as reliable results. As can be seen from results, the Cu/SSt in MLP provides highest temperature degree and most uniform TD upside surface of pan that exposed to food in addition it can retain the heat well in compared with others.

There are some Suggestions for optimizing the cookware. From this analysis the result suggests that find the optimum thickness of layers and various alloys of appropriate metals.

After thickness and material of pan the other considerations are the shape and sizes of the pan that causes maximum heat transfer to food and provides the desirable TD.

Another suggestion to optimize cookware and cooking is, compared that which type of heat source consist of burning gas or electrical resistivity, will transfer more energy to cookware and improve the heat source to spread the heat uniformly. Finally thermal stress and thermal expansion in MLP should be considered for MLP manufacturing.

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Behnam Nilforooshan Dardashti was born in Tehran, Iran, in 1974. He got M.Sc. degree in Nuclear Engineering, 1997-2002, and B.Sc in Solid State Physics, 1991-1997. He is currently Instructor-Member of Scientific Board Islamic Azad University Bueen Zahra branch, Qazvin, Iran.

He published several books and articles such as “Full Explanation of electricity physics” 6th edition of Holiday (Azarbad, Tehran, 2007, to be published), “general Physics (Mechanics and Heat)” (Azarbad, Tehran, 2008, 2nd edition, to be published), “Prediction of Film-Boiling Heat Transfer Coefficient Using Modular Neural Network", Nuclear Energy for New Europe, 2006, NENE-620etc. His areas of interest include heat transfer, Fluid mechanics, Muon catalyzed fusion.

Mohammad Reza Sedighi was born in Tehran, Iran, in 1988. He is studying Mechanical Engineering Fluid Thermal Approach in IAU Karaj branch. He joined Young Researchers Club, Bueenzahra branch since 2008 up to now. He published “*Numerical Solution of Heat Transfer In Single and Multi-Metal Pan,* Applied Mechanics and Materials”. His research interests include Heat transfer, Computational Simulation and CFD applications in heat transfer and fluid dynamics science.