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THERMAL ANALYSIS OF BIMETAL PLATES AS COOKING POTS: COMPUTATIONAL COMPARISON OF TWO GEOMETRIES

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Abstract. Multi-layer-plate (MLP) provides improved thermal, chemical and mechanical properties. High temperature degree, uniform Temperature Distribution (TD), heat capacity and inertness of utensil material are significant parameters in cooking. In this study the main objective is analysis of the TD all over the two different structure of cookware. Analyzed structures have different behavior so we can use them in different propose. In another part we concerned about heat loss from heated cookware. We compared the insulated pan with non-insulated pan. Based on results the insulator improved the heat retaining of pan. It reduces the energy consumption. We employed Finite Element Method (FEM) for analyzing transient thermal behavior of models.

1. Introduction

We can meet the wide variety of demands such as superior mechanical and thermal properties by using multi materials together [1, 2]. Multi-layer structure and material properties of the layers have high impact on improving thermal behavior of cookware. 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 multi-layer plate causes regular TD on the top while bottom heated irregularly [3-5].

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 [6]. 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 while some materials like stainless steel, the least reactive of all popular materials used in cookware, also has the low thermal diffusivity. Stainless steel is durable, non-porous, nonreactive and resistant to rust, corrosion and pitting. Titanium has good corrosion and chemical resistance too. 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 such as stainless steel or titanium therefore safe to use with any food product in layer of pan which is exposed to food [7, 8].

Reference [9] 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 [10] for the stainless steel and titanium in second layer, the TD are almost equivalently in steady state.

In this paper, we used bi-layer pan by bonding highly conductivity and low-reactive materials consist of Al/Cr-Ni, Al/SSt, Al/Ti, Cu/Cr-Ni, Cu/SSt and Cu/Ti. Two different structures are compared with each other. In one of them, the pan wall is made of low-conductive second layer materials of plate whereas in another one, the metal of pan wall is as same as high conductive first layer metal. We compared these two structures with each other to find the differences and suitable performance of these structures and metals.

In another part we concerned about heat loss from heated cookware. We reduced the heat loss by insulting the cookware up to about 20 degrees.

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

2. Materials and methods

Since we want to model irregularly heating, we constrained annular part of the circular surface of bottom side of pan, which illustrated in Fig. 1 as Δr, by constant temperature about 773 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 center of plate along the y-axis have zero value. Hence there is no heat flux at the center of plate along the y-axis. The side of pan has convection heat transfer with air at ambient temperature. We have taken thickness of layers according to Table 1. Parameter Δr is 2 cm. The ambient temperature and the coefficient of heat transfer have been assumed as 293 K and 17 W/ (m^2 K), respectively.

Table 1. Symbols and thicknesses of metals.

Metals	Symbols	Thicknesses, mm
Copper	Cu	8
Aluminum	Al	6.5
Titanium	Ti	2
Chromium- Nickel	Cr-Ni	2
Stainless Steel	SSt	2

Table 2. Density and thermal properties of metals [11].

Symbol	ρ, kg/m^3	K, W/(M K) C, J/ (kg K)	K, W/(M K) C, J/(kg K)
		T=400K	T=600K
Cu	8933	393 397	379 417
Al	2700	240 949	231 1033
SSt	8055	17.3 512	20 559
Cr-Ni	8400	14 480	16 525
Ti	4500	20.4 551	19.4 591

In addition, it is also assumed that the pan is filled up by water at boiling temperature, and the coefficient of heat transfer between the pan and the water is 50 W/ (m^2 K).

Two different structures are compared with each other. In one of them, the pan wall is made of low conductive second layer material of plate (Fig. 1), whereas in another one, the metal of pan wall is as same as high conductive first layer metal as shown in Fig. 2.

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 only with air in ambient temperature for cooling.

In last part we surveyed the influence of insulator on enhancing the heat retaining of cookware. We chose only model 2 for analyzing. We covered the side of pan by insulator illustrated in Fig. 3. In addition, we assumed the pan has a lid so the heat loss will not take place in inner space of pan.

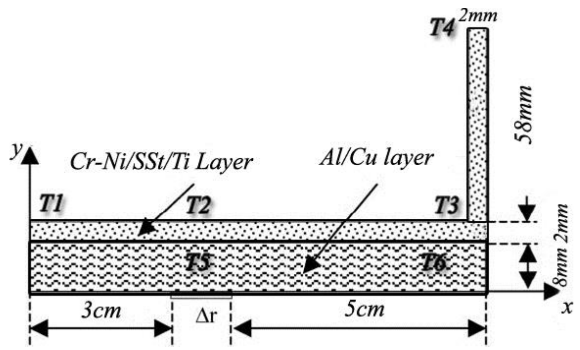

Fig. 1. 2D bi-layer model in numerical analysis and positions of different selected nodes, named T1-T6; model 1.

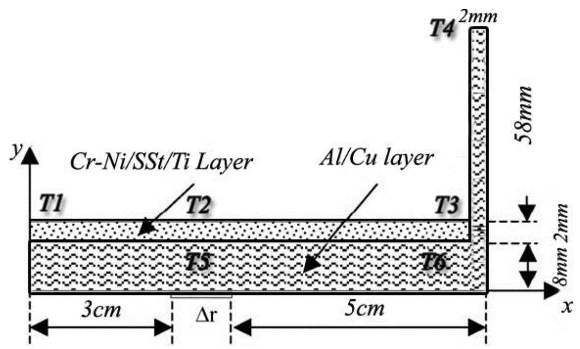

Fig. 2. 2D bi-layer model in numerical analysis and positions of different selected nodes, named T1-T6; model 2.

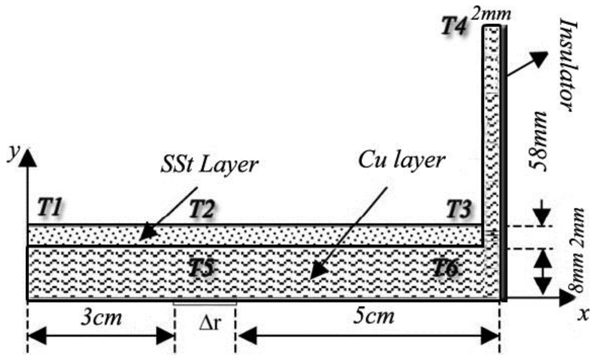

Fig. 3. 2D bi-layer model which is covered by insulator in numerical analysis and positions of different selected nodes, named T1-T6; model 2.

3. Results

A. Temperature distribution in different materials. We used bi-metal structure consist of Cu/SSt, Cu/Cr-Ni, Cu/Ti, Al/SSt, Al/Cr-Ni and Al/Ti. It is predictable that minimum temperature observed at edge of wall. We put the T4 point at edge of wall as a basis for assessment of temperature level of different combination bodies. It is clear that the T4 node temperature in model 2 is higher than model 1 because of high conductive material of wall in model 2 illustrated in Fig. 4. Figure 4 shows that the bi-metal plates consist of copper have the higher temperature than aluminum. In the other hand the titanium has special effect on temperature distribution. Al/Ti in first 50 seconds of analysis has maximum temperature degree in both models. Ti in model1 has higher impact on TD than model 2 because T4 node is in titanium zone in model 1.

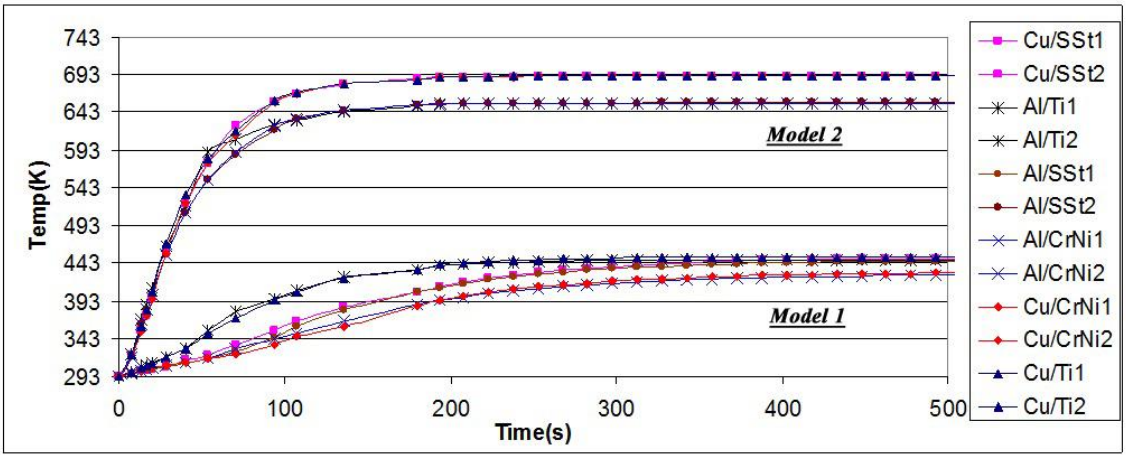

Fig. 4. Temperature variation comparison of T4 node for all bi-metal in model 1 and model 2.

The temperature degree of bimetal structure consist of copper is higher than aluminum at steady state. Figure 4 represents that the minimum temperature of bimetal plates consists of copper in model 2 are almost equivalently. The temperature of T4 node of Cu/SSt at steady state in model1 and model 2 are about 451.1 K and 691.2 K, respectively.

B. Comparison of thermal behavior of Cu/SSt in model1 with model 2. Cu/SSt, Cu/Ti and Cu/Cr-Ni make equivalent thermal behavior approximately. The Cu/SSt satisfies different demand of cooking in field of thermal, chemical and mechanical properties [12]. Hence we selected the Cu/SSt as a sample for comparing different behavior of the two models.

Figure 5 shows that the model reached to steady state after about 200 seconds. The T1 and T2 nodes are closer to heat source than T3 and T4. Hence temperature variation of T1 and T2 are sharper than T3 and T4.

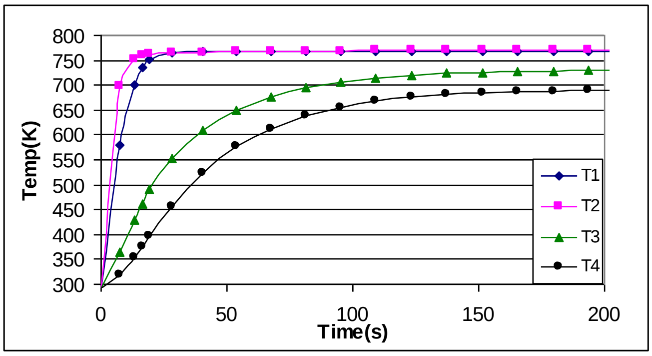

Fig. 5. Time variation of temperature in Cu/SSt model 2.

Figure 6 represents the differences between time variation of temperature of T2 node in model 1 and model 2. The heat tends to transfer through the copper layer which has high thermal conductivity. Hence the wall of model 2 is heated faster and higher than model 1. Figure 6 shows the temperature of T2 node in model 2 is greater than model 1. The reason is the temperature of model 2 wall is higher than model1 wall so temperature gradient in model 2 becomes less than model 1. Subsequently the low temperature of wall in model 1 causes the high heat flux to the side of pan. Hence the heat distributes from center to side. In another word the temperature of T3 zone in model1 is lower than model 2 so the heat distributes from the T2 zone to T3 zone. Subsequently the temperature of T2 zone in model 1 is lower than model 2 while T3 zone temperature in model 1 is higher than model 2 but in model 2 the heat is concentrated in T2 zone. Consequently the T2 node in model2 has higher temperature degree than model1 whereas the T3 node has lower temperature than model1 illustrated in Fig. 7.

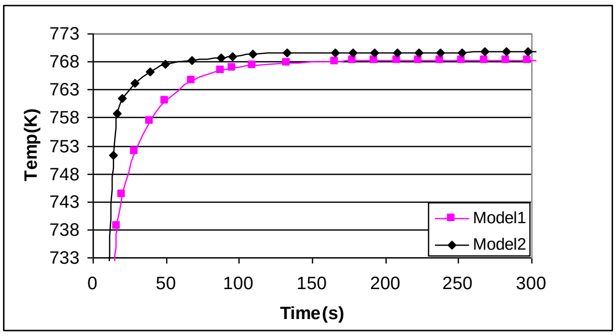

Fig. 6. T2 node temperature changes of model 1 and model 2 over time in the range of 733 to 773 K.

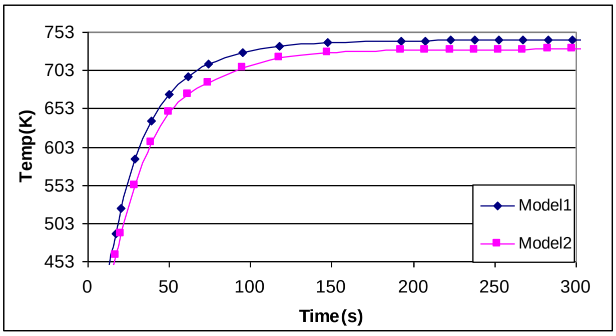

Fig. 7. T3 node temperature changes of model 1 and model 2 over time in the range of 453 to 753 K.

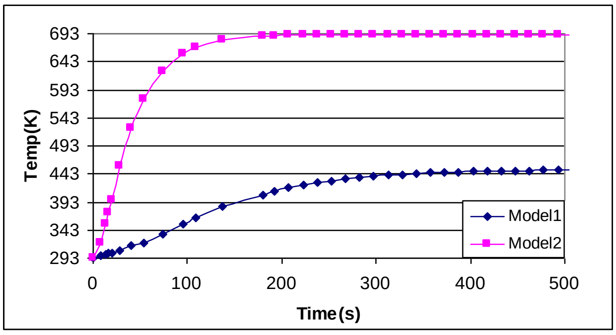

Fig. 8. Time variation of T4 node temperature in model 1 and model 2.

It is clear, temperature of T4 node in model 2 has higher temperature degree because the metal of pan wall in model 2 is copper or aluminum which has higher thermal conductivity than model 1 shown in Fig. 8.

C. Heat retaining. After that the model reached to steady state we changed the boundary conditions of pan to analyzing the heat retaining of the models. Hence we modeled the heated pan to transfer the heat only with air in ambient temperature for cooling. The results of this analysis are illustrated in Fig. 9 for Cu/SSt. Reference [9] represents the heat storing differences of different metals. It shows that the pans consist of copper can retain the heat better than others even gray cast iron. Hence we have used the Cu/SSt to show the different behavior of the two models.

Figure 9 shows that the model1 has higher temperature degree than model 2 at the same time in cooling step. But both of them reach to ambient temperature at the same time.

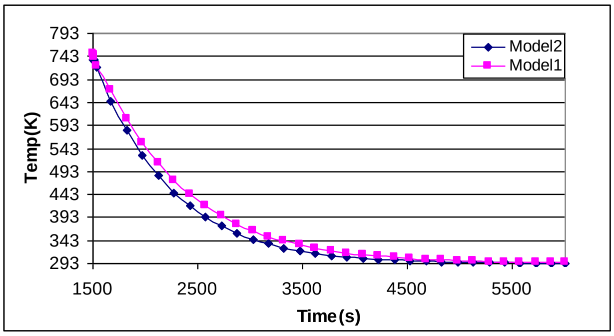

Fig. 9. Comparison of temperature variation of T6 node for model 1 and model 2 of Cu/SST in cooling step.

In model 1 you see that temperature of T4 node is increased firstly and then decreased because T4 node has very low temperature in compared with all over the pan so there is a high heat flux from high to low temperature degrees illustrated in Fig. 10.

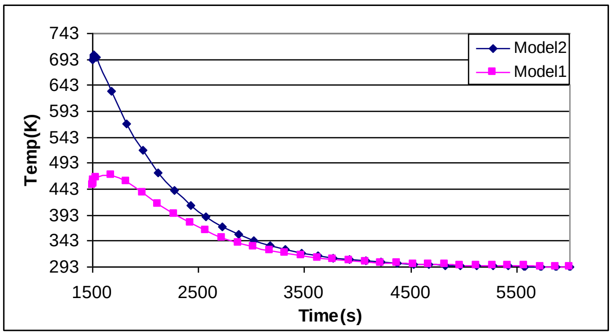

Fig. 10. Comparison of temperature variation of T4 node for model 1 and model 2 of Cu/SST in cooling step.

D. Comparison of thermal behavior of insulated with non-insulated cookware. Figure 11" shows time variation of differences between temperature of T1-T6 nodes of insulated and non-insulated pan in cooling step. First the pan heated to reach steady state. Then we eliminated heat source and the heated pan is exposed to air at ambient temperature.

In this part we used only model 2 and we considered the pan has a lid in cooling step so it has not taken place any heat loss in inner space of pan. The insulated and non-insulated pan with lid reached to ambient temperature during 7500 seconds. Differences between temperature of insulated and non-insulated pan in selected nodes in some minutes during cooling step is up to 20 K shown in Fig. 11. In all nodes we observed that insulated pan has higher temperature degree than non-insulated pan. It is clear insulated pan can store the heat better than non-insulated. We observe that all nodes have relatively same temperature variation.

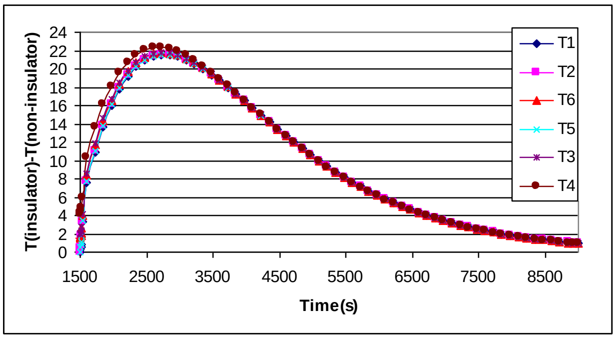

Fig. 11. Time variation of differences between temperature of T1-T6 nodes of insulated and non-insulated pan in cooling steps.

4. Discussion

We analyzed the result of mode l1 and model 2. The temperature distribution of model 1 on cooking surface is more uniform than model 2. We compared the uniformity of temperature distribution on cooking surface of Cu/SSt model 1 with Cu/SSt model 2 as shown in Fig. 12. This figure shows that the temperature distribution of model1 at some time near 50 degrees and at steady state about 15 degrees is more uniform than model 2.

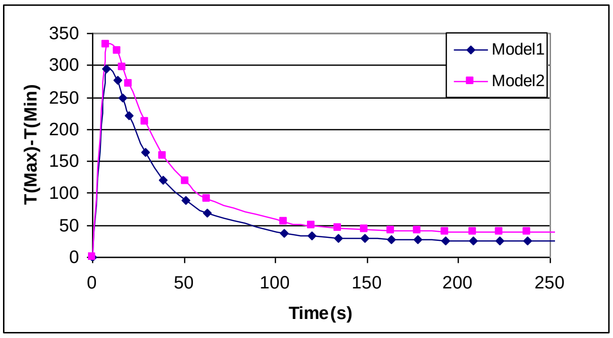

Fig. 12. Time variation of differences between maximum and minimum temperature on food preparation surface of Cu/SSt in model 1 and model 2.

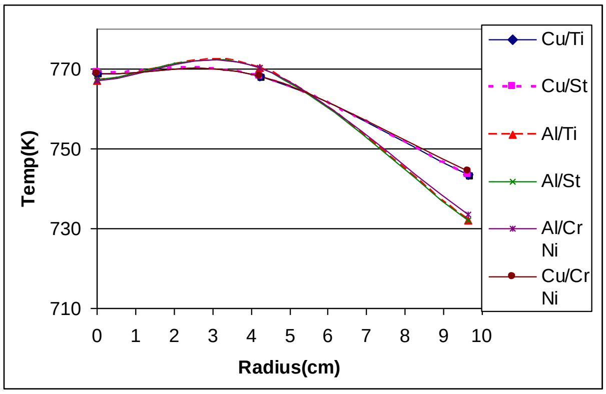

Fig. 13. Temperature distribution on food preparation surface of pan for used metals at steady state in model 1.

Figures 13 and 14 present the temperature distribution on food preparation surface of cookware for all used metals in steady state in model 2 and model 1. These figures show that temperature distribution of model1 is higher and more uniform than model 2. In addition the uniformity of bimetal structures consist of copper is higher than aluminum.

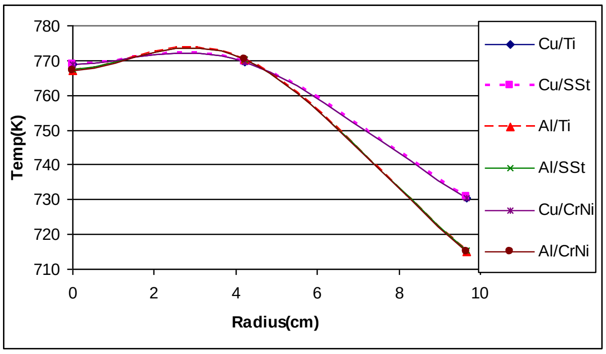

Fig. 14. Temperature distribution on food preparation surface of pan for used metals at steady state in model 2.

The temperature of T2 zone in model 2 is higher than model1 while T3 temperature is lower. Hence we compared these two temperature points with each other to find which model provides higher temperature degree on the cooking surface. First, we calculated the temperature differences of T2 zone between model1 and model 2 over time. Then we calculated this differences for T3 node too. Finally, we subtracted the temperature differences of T3 zone between two models from T2 as represented in equations 1-3 and Fig. 15.

$$T2(t)_{Model1} - T2(t)_{Model2}, \tag{1}$$

$$T3(t)_{Model1} - T3(t)_{Model2}, \tag{2}$$

$$(T3_{Model1} - T3_{Model2})_t - (T2_{Model1} - T2_{Model2})_t. \tag{3}$$

Figure 15 compared the variations of temperature differences of T2 between model 1 and model 2 with the temperature differences of T3 node between these two models over time. According to the figure it is observed that average temperature of model 1 is greater than model 2.

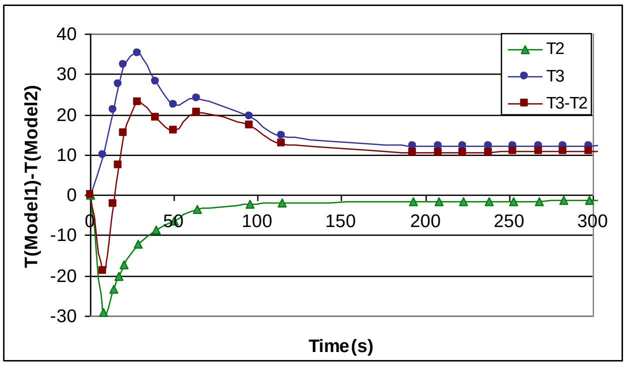

Fig. 15. Time variation of differences of T2 temperature in model 1 and model 2 with the differences of T3.

5. Conclusion

This paper describes the numerical, finite element method, analysis of transient thermal behaviors of multi-layer plate. We analyzed the temperature distribution of cookware which the metal of pan wall is as same as high conductive first layer metal (model 2). Then we compared this model with the model which pan wall is made of low conductive second layer material of plate (model 1). Based on results thermal behavior of plate could be improved by slightly changing in structure. Model 1 provides more uniform temperature distribution on cooking surface than model 2. In addition average temperature on cooking surface of model 1 is higher than model 2 although the temperature of side (wall) of model 1 is lower than model 2. Model1 stores the heat better than model2 too. Consequently model 1 has better performance as cookware which has frying, roasting, etc. application. In this application, cooking surface play key role in cooking and the food do not expose to side of cookware like frying pan, skillet, etc. In the other hand although the temperature degree and uniformity of temperature distribution of model 2 is not as good as model 1 but wide amount of energy can be transferred to food by side (wall) of model 2. Therefore we can use the structure of model 2 to produce such a cookware that is contained water, milk, rice, etc., which is exposed to side of cookware like pot, Dutch oven, saucepan, etc.

Then we insulated the side of model and compared the result with non-insulated model. It is observed that differences between temperature of insulated and non-insulated pan in some minutes during cooling step is up to 20 K.

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