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Numerical modeling of temperature distribution in a high temperature sintering furnace

Yüksek sıcaklıklı sinterleme fırınında sıcaklık dağılımının sayısal olarak modellenmesi

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Abstract

The development of new energy management systems for sintering processes with high energy consumption and generally carried out with traditional recipes has become an important research topic nowadays. It has been focused on homogeneous temperature distribution in the furnace used in the sintering process. If the temperature difference is high in the furnace, the internal structure of the materials can show serious changes. In this study, transient numerical design and analysis were carried out from room temperature to 1100 °C. The temperature changes of the samples placed at different locations in the furnace with the dimensions of 1070x1580x1030 mm were numerically investigated as transiently. In numerical studies, room temperature and initial furnace temperature were defined as the initial conditions. The boundary conditions are given as heat flux on the heater surfaces and convection outside the furnace. At the end of numerical solutions, temperature values were found inside the furnace and on the samples transiently. It was showed that the temperature differences between the samples were high that is expected at the beginning, but these differences decreased to about 17 °C in the steady conditions. Unlike the studies in the literature, the condition of the samples in a protected chamber, not under the influence of direct radiation, was examined and it was observed that the temperature differences decreased by up to 2 °C. In the analysis, time-dependent temperature distributions and temperature differences are given comparatively for two different cases.

Keywords: S2S radiation, CFD, Sintering furnace, Unsteady thermal analysis.

Öz

Yüksek enerji tüketiminin olduğu ve genelde geleneksel reçeteler ile sürdürülen sinterleme prosesleri için yeni enerji yönetim sistemlerinin geliştirilmesi günümüzde önemli bir araştırma konusu haline gelmiştir. Sinterleme işleminde kullanılan fırın içerisinde homojen bir sıcaklık dağılımı için sayısal modellemeler üzerine yoğunlaşılmıştır. Sıcaklık farkının yüksek olduğu durumlarda fırın içerisinde bulunan malzemelerin iç yapısı ciddi değişiklikler gösterebilmektedir. Bu çalışmada oda sıcaklığından 1100 °C sıcaklığa kadar zamana bağlı bir sayısal tasarım ve analiz gerçekleştirilmiştir. 1070x1580x1030 mm boyutlarındaki fırın içerisinde farklı konumlara yerleştirilen numunelerin zamana bağlı olarak sıcaklık değişimleri sayısal olarak incelenmiştir. Sayısal çalışmalarda başlangıç koşulları olarak oda sıcaklığı ve başlangıç fırın sıcaklığı tanımlanmıştır. Sınır şartları olarak ise ısıtıcı yüzeylerinde ısı akısı ve fırın dışında taşınım olarak verilmiştir. Sayısal hesaplamalar sonunda zamana bağlı olarak fırın içerisinde ve numunelerin üzerinde sıcaklık değerleri bulunmuştur. Zamana bağlı olarak numuneler arasındaki sıcaklık farkları başlangıçta beklenildiği gibi yüksek ancak kararlı hale gelindiğinde bu farkların 17 °C'ye kadar düştüğü gözlemlenmiştir. Literatürdeki çalışmalardan farklı olarak numunelerin doğrudan ışınım etkisi altında olmayıp korunaklı bir hazne içerisindeki durumu incelenmiş, sıcaklık farklarının 2 °C kadar düştüğü görülmüştür. İki farklı durum için yapılan analizde zamana bağlı sıcaklık dağılımları ve sıcaklık farkları karşılaştırmalı olarak verilmiştir.

Anahtar kelimeler: Yüzeyden yüzeye radyasyon, HAD, Sinterleme fırını, Zamana bağlı ısıl analiz.

1 Introduction

Heat treatment time is a parameter of the heat treatment process which effects the microstructure and mechanical properties of materials [1]. On the other hand, it is very important that the temperature distribution within the sintering furnaces and the minimum/maximum temperature differences are low according to the time in terms of reducing the heat treatment times, energy saving and operating costs. The internal structures of the sintered materials show serious changes according to the rate of temperature change, the exposure time and temperature differences [22]. For this reason, it is clear that the stabilization of the materials under a homogeneous temperature distribution lead to a decrease in the differences of the material properties in the furnace [2],[3]. Experimental measurement of the temperature distribution is not often possible in terms of in the high furnace temperatures, or measurements can only be made in certain parts of the furnace. In fact, due to the radiation between the samples in the furnace, it is not possible to measure the significant temperature differences experimentally at the beginning. In numerical studies, these limitations are not in question, and reasons such as gaps between samples can be easily overcome with different sample numbers in each region of the furnace. In addition, it is an important advantage that the heater geometry, position and power can be designed as desired, unlike experimental studies [4],[5].

The general framework of the studies in the literature is the comparison of the data obtained with a result of experimental and numerical studies [6]. Many of the numerical studies involve the results obtained by changing the boundary conditions, initial conditions and furnace geometries [7]-[10]. These studies include the commercially ovens such as electric food cooking ovens, paint ovens or fired ovens [7]. Experimental and numerical studies in high temperature sintering furnaces are very few compared to other studies. This

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is due to the difficulty of obtaining experimental data from inside the furnace at high temperatures [1],[13],[15]. Kang and Rong verified the experimental data with a numerical model and examined the effect of material positions and numbers in the furnace. In this study, the materials to be sintered were examined with two different loading methods and the radiation heat transfer rates between these states were showed. As expected, as the distance between samples increases, the effect of radiative heat transfer decreases as well [1]. Li et al. shown that the energy savings can be reduced by approximately 31.9% as optimizing parameters such as heater location, type and size for the oven that they all numerically modeled [15]. In another study, the same researchers emphasized the importance of numerically modeling a large-scale sintering furnace before manufacturing, and it was showed that furnace production with low-cost and more performance could be achieved [16].

In many studies, the effect on temperature distribution of furnace interior geometry and gas flow has been investigated [18]. Minea showed that there could be an improvement of approximately 31% in the heating time by changing the radiant panel angles in the furnace [7],[19]. Wang and Yuan investigated the gas flow and the temperature distribution in vacuum sintering furnaces. In the study, it was showed that the gas flow directions to cause the differences in the temperature distribution. In addition, the effects on the temperature distribution of these gaps were investigated by changing the space between samples [8],[11]. Cosentino et al. performed the numerical analysis for the furnace used in the heat treatment of all super alloys. In their studies, the investigated parameters are the effects of heat transfer, temperature distribution and heat transfer coefficients before the experimental studies [12]. Maniere et al. showed that the heat transfer mechanisms affecting the all sintering process and the geometry of the sample has an effect on the temperature distribution as well as the sample location. It has even been shown that for samples with large volumes and complex geometries, serious temperature differences occur in the furnace and between samples [9]. Oh et al. showed that 4.85%, 14.9% and 2.28% improvement was achieved for the distance between heaters and samples, insulation thickness and wall surface emissivity values, respectively [20].

In the literature, researchers on high-temperature industrial furnaces used for sintering high-tech materials are limited. In order to obtain a homogeneous temperature distribution in the studies, the effects of temperature distributions in the furnace, heat transfer mechanisms, heater and sample locations, insulation resistance, and wall surface emissivity rates were investigated. It has been observed that the resistances in the furnace have a direct effect on the temperature distribution, and the samples are exposed to temperature changes suddenly and high temperature differences under the influence of direct radiation close to the heaters. In this study, a closed chamber was designed in the furnace so that the samples are not under the direct radiation effect. The lateral surfaces of this chamber only see the heaters and indirect radiation is provided to the samples. With this design, it is ensured that the temperature differences in the samples during the first heating process of the materials are small and the internal structure defects that may arise from the high temperature difference in the samples are prevented. The temperature differences in the samples were compared with the chamber condition, the no chamber condition and the experimental result [21]. It was defined as 6 W/m2K convection coefficient for the outer surface to the furnace walls outside the chamber, heat flux (W/m^2) only to the heater surfaces for the inner surface and 0.95 for the emissivity. The heat flux defined to the heater surfaces was calculated as a total power of 40 kW by associating with the total heater surfaces. The numerical model was solved with Ansys Transient Thermal software and the results were compared with Comsol Multiphysics software. The study was carried out in three dimensions (3D), and the surface to Surface (S2S) model of radiation interaction of the samples and the chamber was defined. The emissivity (ε) is defined as 0.77 for the furnace inner wall surface, 0.95 for the heater surfaces and 0.66 for the sample surfaces [21].

2 Model description

2.1 Materials and methods

The sintering furnace used in the numerical model and experimental study is Ipens brand sintering furnace. The dimensions of the furnace and the positions of the samples in the furnace are designed to be exactly the same like reference study. Furnace general dimensions are given in Figure 1 and furnace materials and properties are given in Table 1. Based on the studies of Liu et al., who carried out an experimental study on this geometry and material, the numerical boundary conditions were defined as in these studies. In the experimental study, finite element based COMSOL software was used for numerical analysis to verify the experimental results [21]. In this study, two different numerical models were designed.

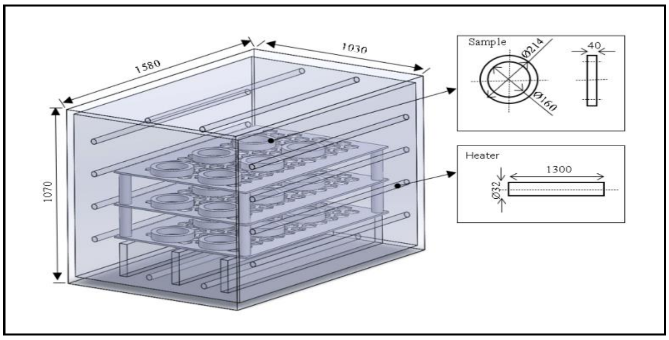

Figure 1. Geometric features of the furnace (Model 1).

The dimension of Model 1 geometry was obtain from the study of Liu et al. Model 2 is the case where a chamber is added that prevents the materials from seeing the heaters directly, but the geometry of the sample and furnace is the same. The convergence between these two numerical designs and with the experimental study in the literature was compared. Boundary and initial conditions were defined as similar in the reference study.

Table 1. Thermophysical properties [21].

Component	Material	ρ (kg/m^3)	k (W/m. K)	cp (J/kg.K)	ε
Insulation	Graphite Felt	120	0.35	350	0.77
Heater	Graphite	1700	180	1850	0.95
Table	Steel	7670	24	700	-
Sample	M50NiL Steel	7820	25	850	0.66

There are 12 electrical resistances with a diameter of 32 mm, a length of 1300 mm and a power of 40kW in the furnace for Model 1. These heaters are placed cylindrically at equal intervals on the lateral surfaces of the furnace inner wall as shown in Figure 1. The design of the samples was made on the support tables placed on top of each other at equal intervals in the direction perpendicular to the plane (z) symmetrically. The outer wall thickness of oven is 100 mm and other dimensions are 1070x1030x1580 mm. The solid model of the furnace and the samples were created by using SolidWorks software, this solid model was transferred into the Ansys Transient Thermal module and the solution was realized.

Model-2, which has the same dimensions but a shield between the samples and the heaters, has been designed so that the samples are not exposed to direct radiation. This design seen in Figure 2, all dimensions were taken the same as in Model-1 and only the chamber walls were placed between the heaters and the samples. The chamber wall thickness is 25mm and its material is graphite, so as not to create a serious thermal resistance and to withstand high temperatures. Thus, it is aimed that the temperature changes of the samples in the chamber are less than the Model-1 without the chamber, and the temperature differences are less within the time.

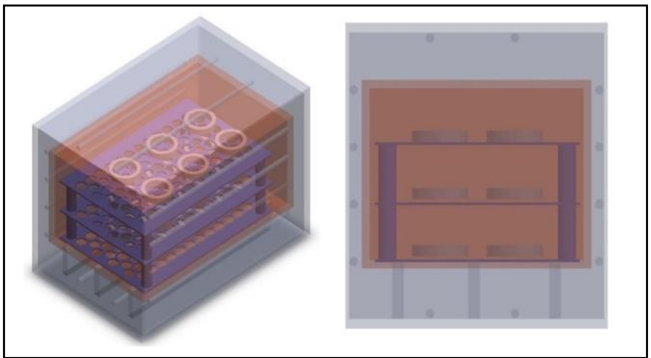

Figure 2. Oven model with a chamber.

2.2 Numerical analysis

The formed chamber (Model-2) and no-chamber (Model-1) furnace geometries were transferred to Ansys Transient Thermal Analysis software. In the numerical model, the samples are designed as ferrules, similar to the comparison study [21]. In order to have less similarities and deviations in comparisons, sample tables were not included in the analysis. In the analysis, the initial furnace temperature was determined as the initial condition, and the boundary conditions were heat flux in the heaters and convection outside the furnace. In the numerical analysis, the furnace outdoor temperature and the convection coefficient were defined as 25 °C and 6 W/m^2 K, respectively. In the interior of the furnace, the heat flux is defined as the boundary condition. As the study was two-stage, two initial conditions were used. The first stage is 26.25 °C and the second stage is 850 °C. The reason for using two different initial conditions is that these values are the initial temperatures in the reference article. In addition, the emissivity values of the furnace inner walls, the sample surfaces and the heater surfaces are defined as 0.77, 0.66 and 0.95, respectively. The reason for making a two-stage solution is that there are few similar studies and the study, which was taken as a reference for comparison purposes, was made under these conditions. In both cases here, the final temperatures are not steady-state conditions and are based on the available final temperatures in the literature for comparison purposes.

Since the effect of convective heat transfer is very small in terms of heat transfer in the inner of the furnace, convective heat transfer is neglected in these analyzes as well [21]. The material properties of the furnace, heater and samples analyzed are as shown in Table 1. Liu et al. used Comsol software in their study and it was stated that the furnace interior was vacuumed in the study. In this study, the spaces between the radiation surfaces are defined as air, but no additional definition of air movement has been made. In the numerical calculations, the transient thermal capacity change of the ambient air inside the furnace is not taken into account. Total heat transfer Surface to Surface(S2S) model was chosen and the results were found in this way.

Thermal radiation is a mechanism of heat transfer that must be considered for heating. Radiation heat transfer governing equations of Ansys software were used for the solution. The net inward radiative heat flux q_r at the solid surface;

$$q_r = G - J \tag{1}$$

$$G = G_m + \sum F_{ext} P_s + \sum F_{ext} q_{0,s} + F_{amb} e_b(T_{amb}) \tag{2}$$

$$J = \rho G + \varepsilon e_b(T) \tag{3}$$

Where G is irradiations, J is radiosity, G_m is mutual irradiation between different boundaries, σ is the Stefan-Boltzmann constant, ε is the surface emissivity, $q_{0,s}$ is the directional radiative sources, P_s is the sum gathers radiation sources located on a point and F is the view factor.

The heating capacity of the furnace is 40 kW and this power is defined as a heat flux of approximately 25000W/m2 to the surface of the heaters. In terms of heat transfer by radiation, Surface to Surface (S2S) option was chosen from the radiation models in Ansys so that the environment in the furnace does not affect the radiation event.

In terms of numerical solution stability, the mesh structure and element dimensions have been changed to ensure independence of the solution from the number of elements. The relationship with the average temperatures over the number of nodes formed depending on the element sizes is given in Figure 3.

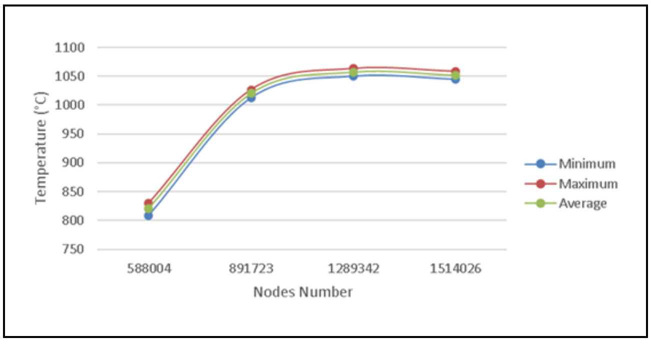

Figure 3. Grid independence test result.

The average temperature used here is taken as the average of the node temperatures on the all samples. As can be seen from this figure, it was seen that the temperatures stabilized after the number of nodes 1.0E+06 and were independent of the number of nodes. The numerical results based on this study showed that the relative variation between temperatures was less than %0.5 at the number of 1.3E+06 nodes. The mesh structure in the model is shown in Figure 4.

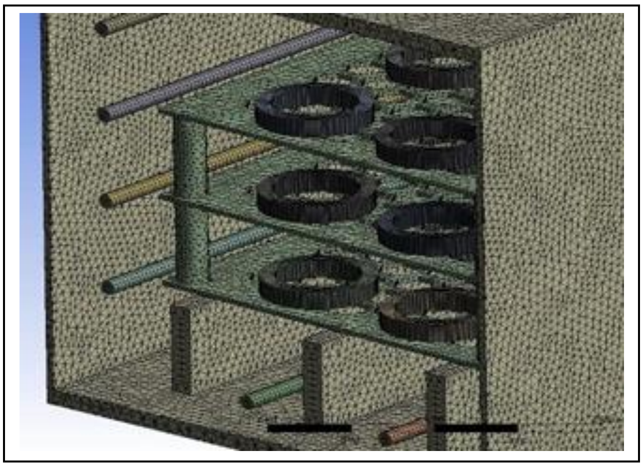

Figure 4. Model mesh structure.

2.3 Model validation

The experimentally obtained transient temperature values in the reference study [21] are shown in Figure 5. As can be seen from the figure, temperature changes in the experimental setup were defined gradually over time and kept constant at certain intervals. In order to compare the results one-to-one, the solution was implemented in two stages. Numerical calculations were made in two parts to compare studies and show the validity of the results. Numerical calculations were made in two parts to compare studies and show validation of results. The experimental study was carried out in the 120-minute section, and the numerical study was carried out between 160-200 minutes.

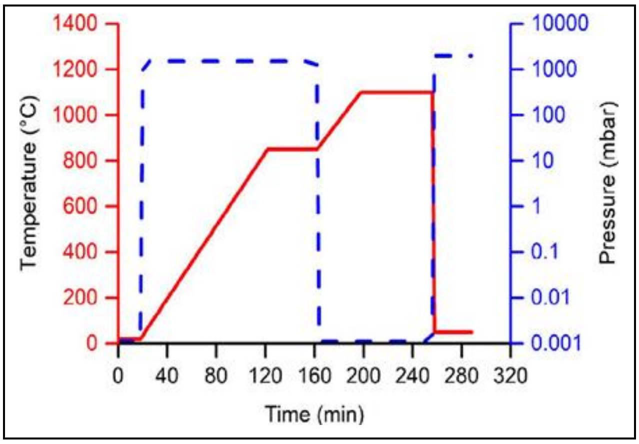

Figure 5. Reference article temperature change [21].

In order to validate this study, the reference study was numerically designed. In the numerical study, the geometry and samples were designed to be the same and analysis was made transiently. Transient temperature changes were defined similar to the experimental study. The numerical analysis results of this study and the experimental results in the reference study are shown in Figure 6 for the first 120 minutes comparatively.

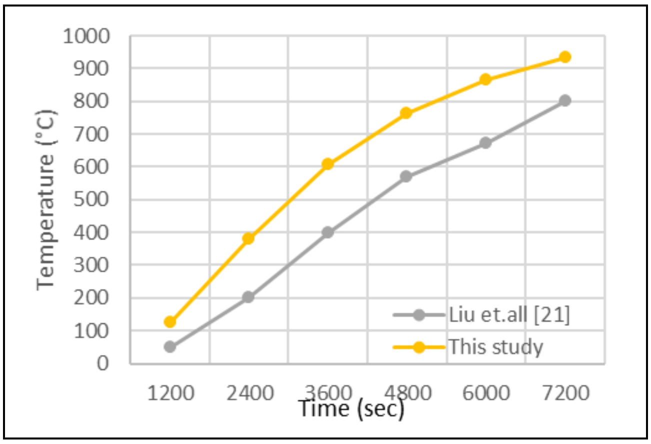

Figure 6. First warm-up phase of 120 minutes.

For the numerical analysis section of reference study, the initial temperature was taken as similar in this study and constant heat flux was defined in exchange for the determined power of the heaters. As a result of these definitions, the variation of the temperature with time obtained from the numerical results is shown in Figure 7. As can be seen from these figures, the path of temperature change overlaps with certain differences. The reason for this is that the stand with the samples was not included in this study and it is thought that it may be due to the inclusion of the furnace walls in the analysis.

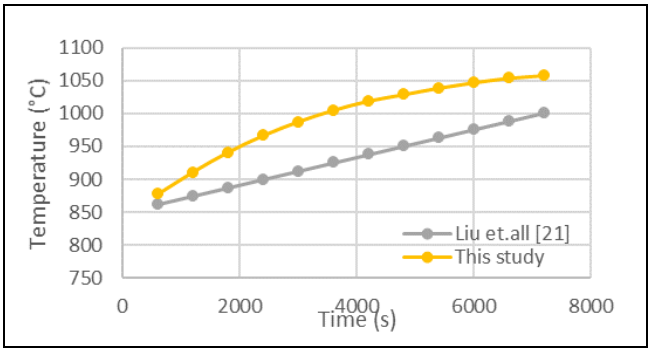

Figure 7. The variation of temperature of sample for an initial temperature of 850 °C.

3 Results and discussion

The scope of the study is to reduce the temperature differences between the samples in the furnace during heating process. For this purpose, a chamber design was made so that the heaters and the samples did not see each other, and it was mentioned as Model 2 in the above sections. Temperature changes for the samples in Model 1 and Model 2 were determined and compared. The average temperatures of the samples were calculated to include one and all of them. As a result, it has been shown whether there is a homogeneous temperature distribution in the furnace. In the studies, analyzes were made for the heaters at constant heat flux, gradual temperature increases and variable heat flux conditions. It was observed that the temperature differences in the chambered condition were smaller than the no chamber condition during the whole heating period and the maximum temperatures remained lower than the no chamber condition.

In numerical analysis, temperature changes at the surface and near the surface are observed as expected, from initial time to stabilization of the outer walls due to the convection boundary condition outside the furnace. It is obvious that these changes will stabilize once they become stable. In Figure 8, temperature distributions for different times on surfaces exposed to convection are given. From this, it is seen that the change is high near the beginning and the isotherm curves do not change in the following periods. This change can also be seen in Figure 9. The reason for this change is due to the convection boundary condition effect, where the minimum, maximum and average temperatures decrease from the beginning to 2400s.

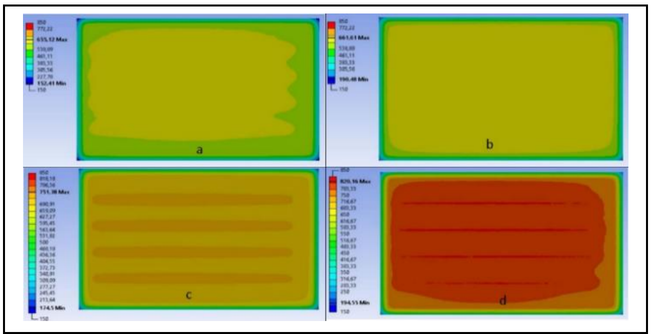

Figure 8. Temperature change in furnace different times. (a): 600s. (b): 1200s. (c): 1800s. (d): 2400s.

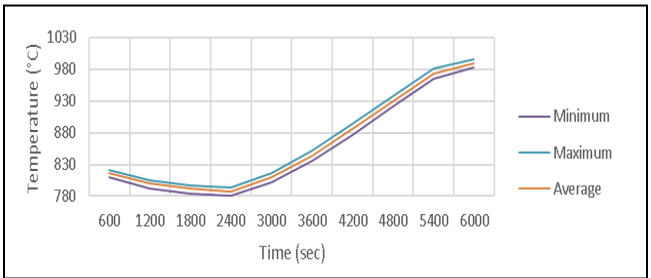

Figure 9. Temperature changes in samples (4 °C/min).

In the analyzes, it has been observed that the temperature difference of the chambered state decreases continuously with a smooth change, but in the other case (Model 1), the temperature difference begins to decrease at a higher value. The temperature differences for both analyzes and the relative percent errors of these temperature differences respect to each other are given in Figure 10. It has been seen that the relative percent error for both cases starts with about 40%. After then, the percentage error value becomes equal with a small error. It is seen that after a certain period of time (3600s), the minimum and maximum temperature differences do not change much and become stable for both cases. It has been determined that the solution is for the state before the steady state, and the temperature differences continue to decrease and do not remain constant.

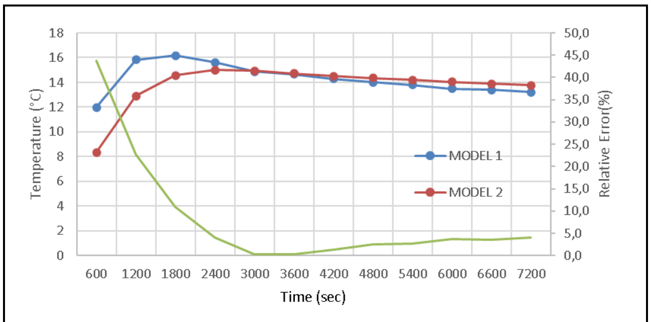

Figure 10. Temperature difference and relative error over the samples.

It is seen that the temperatures in the samples for both cases are initially the same in Figure 11. However, it was observed that the temperature increase in the chambered state showed a more stable, whereas this change was not stable in the no chamber state. In this case, it is clearly seen that direct radiation to samples in sintering furnaces may cause thermal distortions on the samples. This study clearly showed the impact of two conditions on materials.

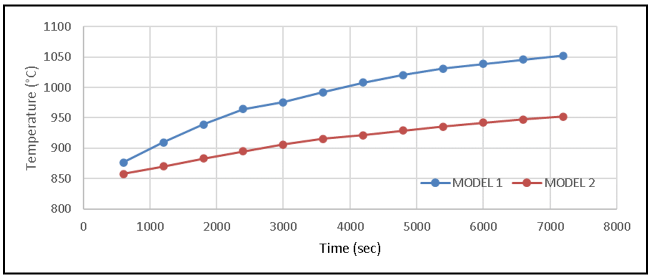

Figure 11. The temperature difference over the samples for Model 1 and Model 2.

It is seen that the temperatures in the samples for both cases are initially the same in Figure 11. However, it was observed that the temperature increase in the chambered state showed a more stable, whereas this change was not stable in the no chamber state. In this case, it is clearly seen that direct radiation to samples in sintering furnaces may cause thermal distortions on the samples. This study clearly showed the impact of two conditions on materials.

The temperature distribution on the samples for both models is given in Figure 12 for the final situation. As can be seen from this figure, as expected, it was observed that the temperatures of samples are high in the near the heater, but the temperatures partially decreased as they moved away from the heater. Analyzes were also made according to sample locations. The temperature distribution of the sample locations is shown in Figure 13. In Figure 14, the average temperature values of the selected sample location are showed as depending the time according to Model 1 and Model 2. It was observed that the temperature change of Model 2 on the samples was lower than Model 1, as shown in the above sections. For Model 1, it is seen that the temperature changes on the samples are high at the beginning, whereas in the other case, it is at a lower level.

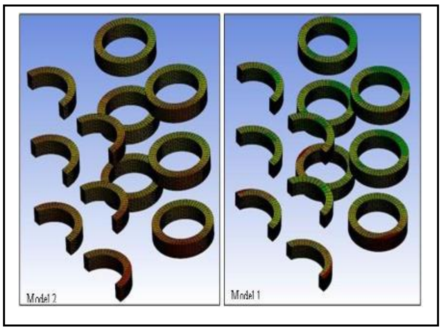

Figure 12. Temperature variation in the chamber model.

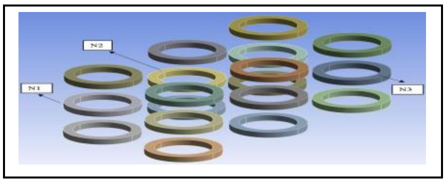

Figure 13. Position of samples inside the furnace.

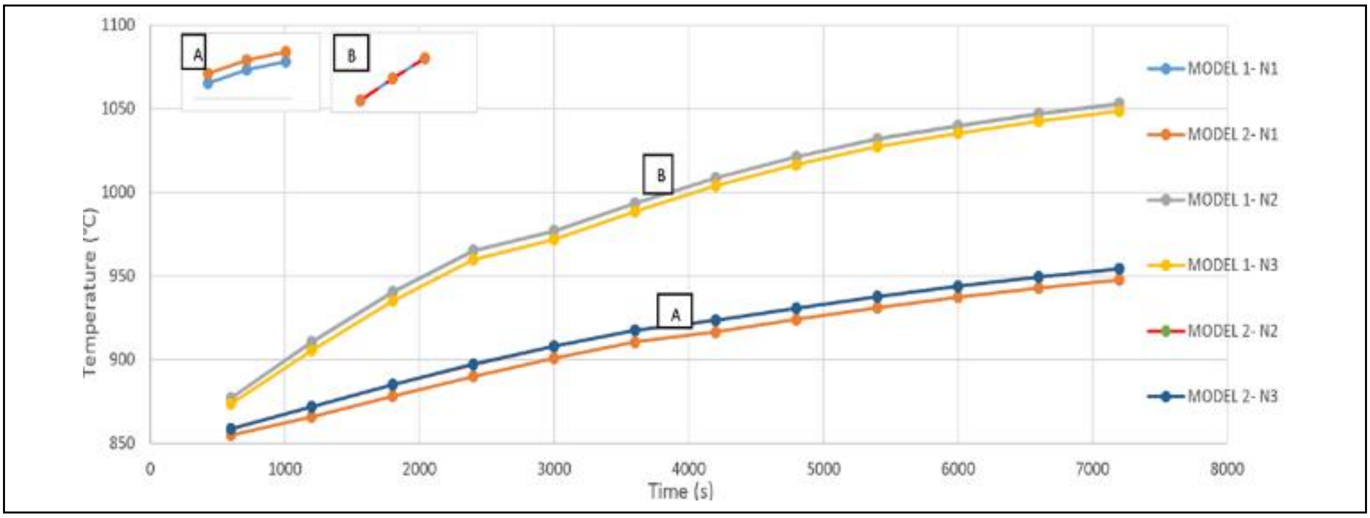

Figure 14. Transient temperature distribution in the selected samples.

4 Conclusion

In this study, the change of sample temperatures in sintering furnaces was investigated. The temperature distribution in the furnace and the temperature changes of the samples in the furnace during the heating process are shown with figures. It has been shown that the results of the study of Liu et al., which was taken as the reference, largely overlap with this study. The results for this study can be summarized as follows:

- ✓ Numerical results have been verified with the reference article consisting of experimental and numerical studies,
- ✓ In the comparison of transient temperature changes (Figure 7), the proportional differences between the results range from 1.7% to 8%. In this case, the numerical model created shows a very good convergence,
- ✓ In order to eliminate the direct heating effect of the heaters on the samples, a new inner chamber design has been proposed for the existing furnace geometry,
- ✓ This chamber design is defined as Model 2 and the temperature changes for this design are presented with figures,
- ✓ In the evaluation based on initial and near to steady-state temperatures (Figure 11), the proportional temperature differences on the samples for Model 1 and Model 2 are determined to be %17 and %10, respectively." This situation indicates, as expected, that the temperature fluctuations in Model 2 are lower compared to Model 1,
- ✓ In the analyzes, it has been shown that a more homogeneous temperature distribution can be obtained by ensuring that the samples are not exposed to direct radiation with the heaters,
- ✓ An error analysis study was carried out for the cases where the samples were exposed to direct radiation or not, and it was seen that the high temperature differences that cause internal structure deformation in the material were less for Model 2.

5 Author contribution statements

In the study carried out, the Türker AKKOYUNLU under the titles of forming the idea, making the design, performing the numerical analysis and literature review; İbrahim UZUN under the headings of evaluation of the results obtained, arrangement of the text and examination of the results; Hüsamettin TAN contributed in the titles of checking the article in terms of spelling and translation.

6 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person / institution in the article prepared”.

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