

## Investigation of Alternative Material and Design of Rotary Kiln: A Case Study

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### Abstract

Rotary kilns have widespread usage in many field of industry due to continues flow and heating the products inside it, simultaneously. Rotary kiln can be used in the process of alumina, cement, lime, magnesium etc. Rotary kiln material for corrosive process media is usually designated as stainless steel. In some media as high temperature and dilute acidic, even stainless steel can be subject to rapid corrosion. In this study, an alternative material, titanium Gr 2, was investigated instead of conventional 316L (1.4404) quality stainless steel material of rotary kiln. Due to the different physical properties of titanium Gr 2 material, two different alternative designs were prepared and analyzed with the model. In the first design the outside of the titanium shell of the rotary kiln was covered with 316L (1.4404) quality steel material. In this design, different thermal expansion of the materials limited the usage of hybrid materials at high temperature. Therefore, as a second alternative the length of the rotary kiln was extended. According to required product output temperature the required of the length extension was calculated as 4600 mm.

**Keywords:** Rotary kiln, Titanium, Heat transfer, Thermal expansion

### Döner Fırının Alternatif Malzeme ve Tasarımının İncelenmesi: Bir Örnek Olay

#### Özet

Döner fırın, içerisindeki ürünlerin sürekli akması ve aynı zamanda ısıtılması nedeniyle endüstrinin birçok alanında yaygın olarak kullanılmaktadır. Alümina, çimento, kireç, magnezyum vb. işlemlerinde döner fırın kullanılabilir. Bu çalışmada fırınların yaygın bir malzemesi olan klasik 316L (1,4404) kalite çelik malzemesi yerine alternatif bir malzeme olan titanyum Gr 2 malzemesi incelenmiştir. Titanyum Gr 2 malzemenin farklı fiziksel özelliklerinden dolayı model ile iki farklı alternatif tasarım hazırlanmış ve analiz edilmiştir. İlk tasarımda döner fırının titanyum kabuğunun dışı 316L (1,4404) kalite çelik malzeme ile kaplanmıştır. Bu tasarımda malzemelerin farklı termal genleşmeleri, hibrit malzemelerin yüksek sıcaklıkta kullanımını sınırlandırmıştır. Bu nedenle, ikinci bir alternatif olarak döner fırının uzunluğu arttırılmıştır. İstenilen ürün çıkış sıcaklığının elde edilebilmesi için 4600 mm boy uzatmana gerek olduğu hesaplanmıştır.

**Anahtar Kelimeler:** Döner fırın, Titanyum, Isı transferi, Termal genleşme

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## 1. INTRODUCTION

A rotary kiln is a combination of large cylindrical steel vessels which is supported by rolling supports. It is slightly inclined in the horizontal axis, and rotates about its axis very slowly [1]. It is used to increase material temperature to a high temperature in a continuous process and its main aim is to drive a reaction at a specified temperature and time [2]. Although there are many methods to produce chemical products, using a rotary kiln is widely preferred due to the dynamic nature of production of goods in chemical, metallurgical and cement industries [3,4]. The rotary kiln can be used to produce cement clinker which is the main product of cement extraction, nickel from saprolite ore, crystallization of sodium chromate, calcination of dolomite pyrolysis and gasification process of oily sludge [5-10]. Therefore, the rotary kiln has an important task in the production line of many goods. Rotation speed, temperature, inclination angle, material flow rate and discharge rate of the kiln are several properties that affect the efficiency of the operation [11].

In literature, there are some studies about the details of the heat and flow in a rotary kiln, however, there are few studies about an alternative design and materials of a rotary kiln. In previous studies, Witt et al. (2018) used a hybrid approach in order to observe dynamic and thermal behaviour of gaseous freeboard and bed [12]. They used a 2D discrete element method (DEM) to measure mean solids velocities in bed and 3D two-phase CFD models to validate the solid rheology method. As a result, they found out that the procedure could be used for large-scale rotary kilns. Yin et al. (2014) developed a mathematical model based on a three-dimensional model to understand the particle motion characteristic in a rotary kiln [13]. Their model was based on the Eulerian and kinetic theory of granular flow method. They concluded that the bed surface tilted and became slightly S-shaped. Moreover, they found out that the particle velocity reached the highest magnitude at the free bed surface. Gunnarsson et al. (2020) focused on the radiative and convective heat transfer between the gases in the freeboard which includes particle radiation and the kiln wall [14]. They predict the

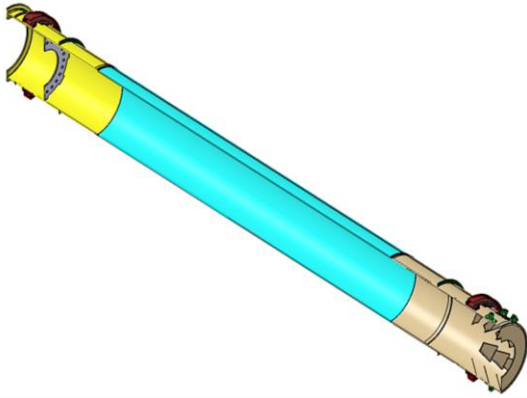
inner wall and bed surface temperatures with less than 11% errors with the model. Boateng and Batt (1996) developed a mathematical model in order to investigate the temperature distribution within the bed and heat transfer from the freeboard gas to the bed of a rotary kiln [15]. Barr et al. (1989) investigated the heat transfer in the cross-section of a rotary kiln. Their mathematical model included all the transport mechanisms of heat transfer processes [16]. The results showed that the high net inputs to the bed material reached at the initial 1.5 m of the kiln length and then the net heat input to the bed material declined. They also suggested that feed should be preheated to a specific level for an endothermic bed reaction in order to proceed the reaction immediately upon the goods entering the kiln. Wulandari et al., investigated the effect of temperature, feed rate, rotating frequency and particle size of the dolomite calcination at a bench scale rotary kiln. Based on the conversion rates and operational temperatures, they found out that at a larger scale, heat transfer plays an important role in the calcination of dolomite [10].

Conventionally, rotary kilns are generally produced with steel material. Stainless steels have a wide application area in industry due to their corrosion and heat resistance and they meet different requirements such as strength, weldability and toughness [17]. In the current system, the main material of the rotary kiln is 316L (1.4404) quality steel. Although 316L (1.4404) quality steel has a good corrosion resistance, the rotary kiln shell is corroded until it becomes unusable in every six months. The aim of this study is to investigate the temperature distribution on a rotary kiln by considering the kiln's material. The alternative material and design to the current system were also examined and they were numerically analysed. Due to the different properties of material, alternative designs were suggested throughout the study.

## 2. MATERIAL AND METHOD

In the current system, the solution enters the rotary kiln at 145 °C and leaves at 215 °C by means of heating the second region of the kiln to 636 °C.

The basic operation properties of the current system was given in Table 1. In Figure 1, the section of the rotary kiln which uses in the current application was illustrated. Although the inside diameter of rotary kiln is 900 mm, in the process, only 200 mm of height from the bottom was filled with the goods.



**Figure 1.** Section of the 3D model of the rotary kiln

**Table 1.** The basic operation properties of the current system

<b>Materials</b>	I. Region	316 L
	II. Region	316 L
	III. Region	316 L
<b>Outside temperature</b>	I. Region	20 °C
	II. Region	636 °C
	III. Region	20 °C
<b>Average input temperature of the goods</b>		145.0 °C
<b>Average output temperature of the goods</b>		215.0 °C
<b>Mass flow rate</b>		0.893 kg/s

In the application the current system of rotary kiln was composed of 316L (1.4404) quality steel. The properties of the material is given in Table 2.

**Table 2.** Properties of 316L (1.4404) quality steel

<b>Chemical composition of 316L (1.4404) quality steel</b>			
<b>C</b>	<b>Cr</b>	<b>Mn</b>	<b>Mo</b>
0.030	16.0-18.0	2.0	2.0-3.0
<b>Ni</b>	<b>P</b>	<b>S</b>	<b>Si</b>
10.0-14.0	0.045	0.03	1.0
<b>Physical properties of 316L (1.4404) quality steel</b>			
Density			7850 kg/m <sup>3</sup>
Modulus of elasticity			193 GPA
Thermal conductivity			16.2 W/m-K
Specific heat			0.50 kJ/kg-K

In the study, titanium Gr 2 material was chosen as an alternative material to the rotary kiln since the material has a higher corrosion resistance than 316L (1.4404). However, due to the stability of the material is limited to 500 °C, the outside temperature of the rotary kiln was decreased to 500 °C. The properties of titanium Gr 2 material was given in Table 3.

**Table 3.** Properties of titanium Gr 2 material

<b>Chemical composition of titanium Gr 2 material</b>					
<b>C</b>	<b>H</b>	<b>Fe</b>	<b>N</b>	<b>O</b>	<b>Ti</b>
≤0.08	≤0.015	≤0.30	≤0.03	≤0.25	Rest
<b>Physical properties of titanium Gr 2</b>					
Density			4620 kg/m <sup>3</sup>		
Modulus of elasticity			105 GPA		
Specific heat			0.52 kJ/kg-K		
Thermal conductivity			20 W/m-K		

In the study, 3D model of the kiln was prepared for numerical analyses. In the analyses material inside the kiln was prepared with boolean operation. Moreover, air inside the rotary kiln was also modelled for the analyses.

The required heat input to the goods inside the rotary kiln may be calculated analytically by means of heat absorbed from the goods and heat lost to the ambient. The heat lost from a rotary kiln to the ambient air occurred through convection and radiation, it can be shown in an Equation 1 as;

$$\dot{Q} = \dot{Q}_{\text{con}} + \dot{Q}_{\text{rad}} \quad (1)$$

Heat lost through convection along the length of rotary kiln with subdivided into a number of  $n$  small segments  $dx$  may calculate from Equation 2.

$$\dot{Q}_{con} = h_n \cdot 2\pi r_o dx \cdot (T_{s,n} - T_A) \quad (2)$$

Where,  $h_n$  is convective heat transfer coefficient;  $r_o$  is the outer shell of the rotary kiln;  $T_{s,n}$  and  $T_A$  are the average temperature of the section and average ambient air temperature.

Heat lost radiation along the length of rotary kiln with subdivided into a number of  $n$  small segments  $dx$  may described as it shown in Equation 3.

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot 2\pi r_o dx \cdot (T_{s,n}^4 - T_A^4) \quad (3)$$

Where,  $\varepsilon$  is the emissivity and  $\sigma$  is the Stefan-Boltzmann constant ( $\sigma = 5,67 \times 10^{-8} \text{W/m}^2\text{K}^4$ )

Due to the kiln rotation, in order to increase the accuracy of the model Equation 4 was used by Sadighi et al. (2011), Gorog et al. (1982) and Agrawal et al. (2017) of the model for values of  $Re_w/\sqrt{Gr}$  greater than 0.2 [18-20].

$$h_n = \frac{0.11\lambda Pr^{0.36}}{D} (0,5Re_w^2 + Re^2 + Gr)^{0,35} \quad (4)$$

### 3. RESULT AND DISCUSSION

During the numerical studies, firstly, the existing conditions were modelled and the results compared both with the measured data in the field and analytical results. According to numerical analyses of existing conditions, the output temperature was found as 216.9 °C. The result of the analyses was shown in Figure 2 below. The desired output of the product is 215±5 °C.

By using titanium Gr 2 material instead of 316L steel material, due to the stability conditions of the material, the outside temperature at heated part (Region II) of the rotary kiln should be decreased to 500 °C. Temperature distribution of the liquid was shown by using titanium Gr 2 was shown Figure 3. According to results, the output temperature of the liquid was found as 191.5 °C. This result is unacceptable for the process. Therefore, other applications was performed in the study. In other system, rotary kiln combined with 316L (1.4404) and titanium Gr 2 materials. In this proposed hybrid system the outside of Region II was covered with the steel material and the inside of the region was covered with titanium material. By this, the outside temperature of the rotary kiln was able to increase to 636 °C. The heat distribution of this system was shown in Figure 4. However due to the different thermal expansion the stress was calculated as 1296.2 MPa which may fail the materials of the kiln. The von-Mises stress distribution of rotary kiln was shown in Figure 5.

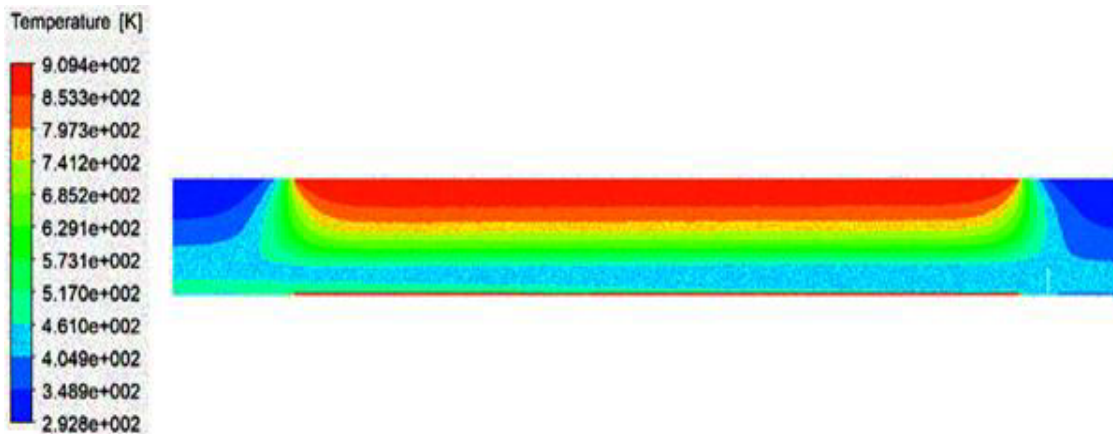


Figure 2. Temperature distribution of the liquid in current system

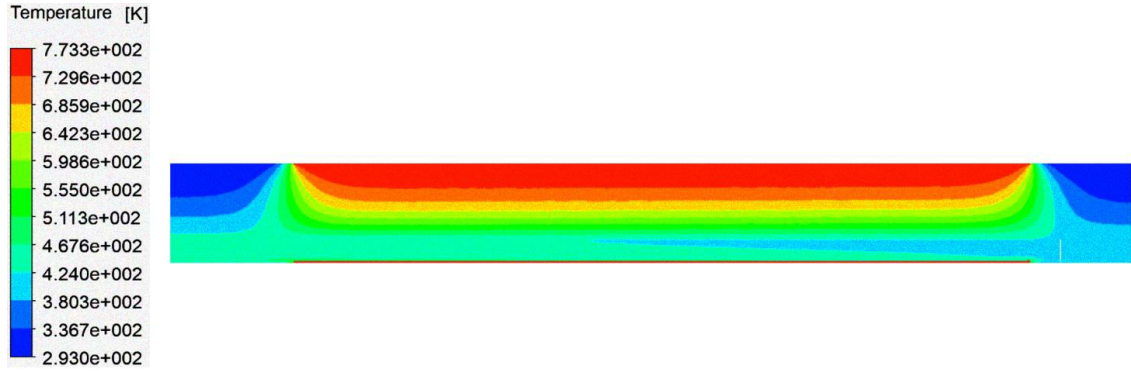


Figure 3. Temperature distribution of the liquid by using titanium Gr2 material.

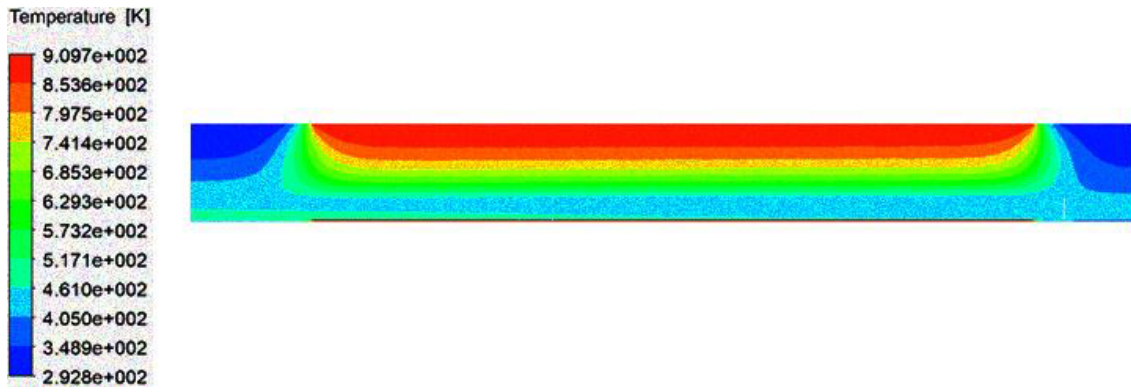


Figure 4. Temperature distribution of the liquid by using the combination of 316L (1.4404) and titanium Gr 2 materials

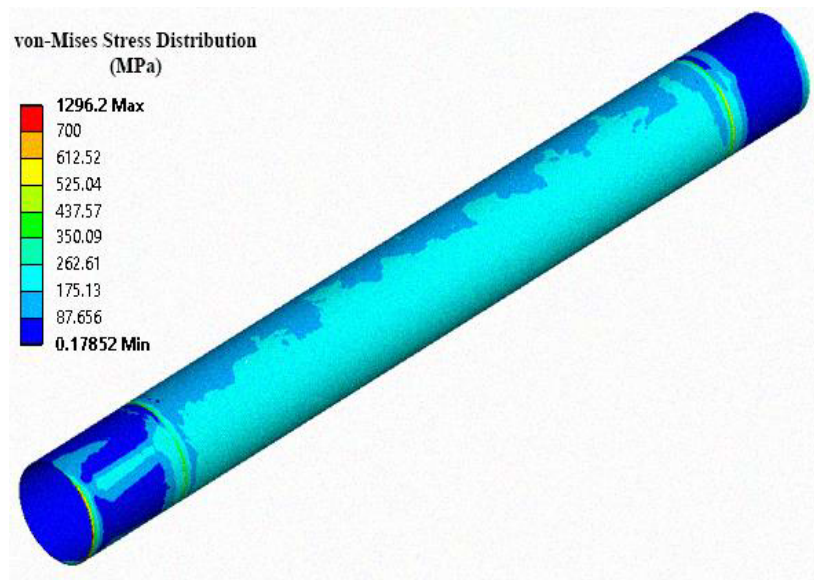


Figure 5. Thermal stress distribution with the combination of 316L (1.4404) and titanium Gr 2 materials

In the last, the length of the region II, which is the heated part from boiler (Region II) was extent by 4600 mm. With increment of the heat input region the output temperature of the fluid was able to reach 214.8 °C and the heat distribution of the

solution was in a good match with current system. Thus, heat distribution was acceptable for the process. The temperature distribution of the system was illustrated in Figure 6.

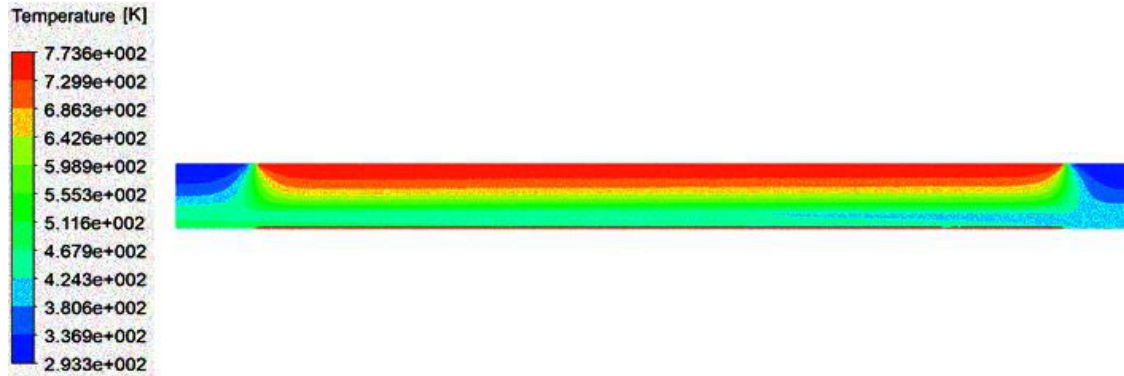


Figure 6. Temperature distribution of the liquid in extended rotary kiln

#### 4. CONCLUSION

The objective of this study was to improvement of a rotary kiln system was performed by using different alternative material and designs. Titanium Gr 2 materials were investigated throughout the study. According to experiments and results, following summarizes were brought out:

- The results of numerical analyses indicated that the output temperature of the product is 216.9 °C,
- Due to the stability temperature of titanium Gr 2 the outside temperature of rotary kiln was decreased to 500 °C. Thereby the output temperature of the product reduced to 191.5 °C, which is not in the desired temperature range.
- A hybrid material was performed in the model which is the combination of titanium Gr 2 material and 316L (1.4404) quality steel at the inside and outside of the rotary kiln shell, respectively. However, the model showed that the usage of the hybrid materials without another material between them is impossible to use due to the high thermal stress.

- In the final, solely titanium Gr 2 material was used as the material of rotary kiln again. However, the kiln was extended by 4600 mm in order to obtain desired product output temperature.

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