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Simulation of a Box Annealing Unit

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Abstract

In this paper the heating process in a box annealing unit is simulated and the effect of various parameters involved in the process is examined. For this purpose, the full Naiver-Stokes equations along with the standard k-ε turbulence model are solved in the fluid region using the finite volume approach. In the solid area the conduction heat transfer equation is employed using approporate surface conductance models. The program used for these calculations was the well known fluent code. The effect of various parameters such as inlet temperature, type of gas used, fan power and coil size and weight are examined. Using the simulation results, it is possible to examine the time variation of the temperature at the critical points, i.e. the temperature at the cold and hot spots. Comparisons of the predicted results with the existing field measurement results were promising.

Keywords: Box Annealing, Flow simulation, Fluid flow, Steel coils

Introduction

Annealing process is an important process in the steel producing industry. By means of this process, it is possible to improve the quality of the final product. The process involves some sort of heat treatment of steel sheet stripes or coils by a flow of a hot gas. Therefore, it deals with a fluid region and a solid area. There are a number of parameters affecting this process. In this process, which is referred to as annealing process, the grain structure of the cold rolled coils is recrystallized at the elevated temperatures to reduce the hardness of the stripe and increase the formability characteristics of the product. To perform the heating action in the annealing process, two different methods are available. In the first method, steel coils are arranged on top of each other inside a vertical cylindrical chamber. This chamber is filled with an inert gas such as nitrogen, and then the whole chamber is put inside a furnace. By means of some burners arranged around the outer furnace, it is possible to heat up the inert gas surrounding the steel coils. A fan circulates the hot gas through and over the coils and transfers heat to coil surfaces. The heat addition to steel coils, removes any residual stresses from the coils and consequently improves their quality. A cross-sectional view of the steel coils, the inner chamber and the outer furnace are shown in Figure 1.

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In the second method of annealing a stripe of sheet metal enters a hot chamber continuously and after being heated, it exits from the other end. However, this method is not referred to in this paper and the first method, i.e. the batch annealing is under investigation. The batch annealing, as sometimes referred to as a box annealing, has been studied by many researchers and the effect of various parameters affecting the annealing process has been investigated. Some of these works are experimental, while some others are analytical or numerical. In the following lines a selected number of these works are presented.

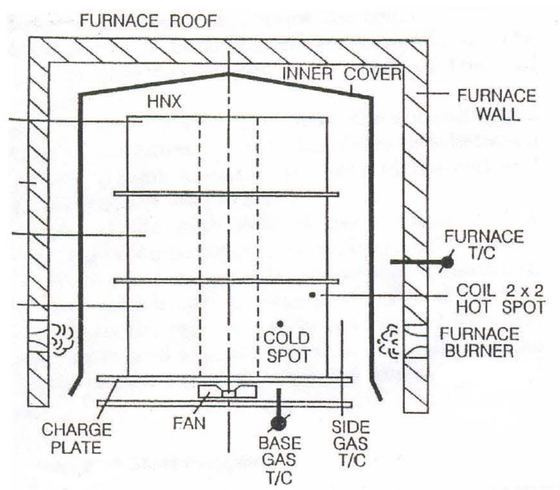

Fig. 1. Arrangements of a box annealing [3].

Meyer and Voelk [1] developed a mathematical model to predict the heat transfer of a tight – coil Bell type furnace. Their model was able to calculate the heat transfer during the heating process in two radial and axial directions. Zecca [2] used a dynamic model to control the box annealing process. In his work, he made use of a mathematical model; and following that he used experimental results to make some corrections to his model. In his model a conduction coefficient was used which was dependent on two radial and axial directions. Then, using analytical relations, he was able to workout the temperature. At the end, he employed a set of fifteen measurement results in order to make better correlations to his equations. Rovito [3] developed a model to predict the end of the time of annealing process. He [4] also developed another model that was able to predict the temperature of the cold spot in a batch annealing process. Thekdi and Wormer [5] were able to design an advanced cooling cover in batch coil annealing and reported a remarkable improvement in the quality of the product. Park et.al. [6] Employed a finite element analysis to simulate a hot rolled coil cooling process. They used this method to analyze the heat transfer in the hot rolled coils, and to determine the equivalent thermal conductivity some experimental results were also used.

Harvey [7] made a mathematical simulation of tight coil annealing which was a continuous annealing process. Also Junius [8] did an analysis of metallurgical and economic aspects of a continuous annealing of cold rolled steel coils.

Normally in box annealing processes, a mixture of nitrogen and hydrogen gases (hereafter referred to as HNX) are used [9]. However, the new trend is toward the use of pure hydrogen [10-11] instead of HNX. Today most steel producers around the world employ pure hydrogen in their annealing process. With pure hydrogen not only is the quality of the product improved, but also the total annealing time is reduced to about 40 to 60 percent of the time used with HNX. It is clear that the annealing time reduction has the direct consequence of energy saving.

From heat transfer point of view, the thermal conductivity of hydrogen is higher than that of the HNX gas. Therefore, the rate of heat transfer from the hydrogen to the steel coils is higher. On the other hand, the density of hydrogen is lower than that of HNX. Hence, the power required with hydrogen gas is higher than that needed with the HNX gas. The extra power needed with the hydrogen gas is about 30 percent more than that with the HNX gas. However, the flow circulation with hydrogen gas is almost three times as high as that with the HNX gas. The higher the flow circulation, the better the radial heat transfer between the gas and the steel coils. Also, with better flow circulation it is possible to have more burners and increase the heat rate.

Another advantage of hydrogen gas is a better surface finish by removing oil from the surface of the metal. The major problem with hydrogen gas is the safety. Any gas leakage will lead to a dangerous explosion with some fatal consequnces [10].

In this paper, attempts have been made to simulate the complicated flow field inside a box annealing unit using computational fluid dynamic (CFD) techniques. With this flow simulation, it is possible to estimate the temperature of the hot and cold spots of the steel coils and also examine the effect of various parameters affecting the performance of a box annealing unit. Comparison of the calculated and field measurement results appeared to be in a reasonable agreement. The geometry of a box annealing unit is shown in Figure 1. As it is shown in this figure, 3 steel coils are located inside a furnace on top of each other, separeted by convector plates. The top coil is designated as coil number 3 and the bottom coil is considered as coil number 1. The convector plates are some circular plates with different shapes of radial slots or grooves. There is a fan underneath the steel coils which sucks the hot gas from the inner channel of the coils and pumps the gas through the outer channel toward the coils. In this paper attempts have been made to solve the governing equations for this geometry and make an estimation of the temperature profile for all coils.

Governing Equations

In this problem, there are two different domains to be considered: a gas flow and a solid region. For the first domain, we have to solve the continuity, momentum and energy equation along with the standard K-ε model to simulate the turbulence flow. In the solid area, the energy equation is the only equation to be solved. The whole system of equations is as follows:

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

Momentum Equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + Fi \qquad (2)$$

Where ρ is density, u_i, u_j are velocity components, P is static pressure, Fi is external body force and τ_{ij} is the shear stress. The shear stress for a Newtonian fluid is as follows:

$$\tau_{ij} = \left[\mu\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial u_i}{\partial x_j}\delta_{ij} \qquad (3)$$

Where μ is the dynamic viscosity.

Kinetic Energy of Turbulence

$$\rho\frac{DK}{Dt} = \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial K}{\partial x_i}\right] + G_k - \rho\varepsilon \qquad (4)$$

Where: K is turbulent kinetic energy, μ_t is the turbulence viscosity, G_K is the turbulence energy generation term, σ_k is the turbulent kinetic Prandalt number and ε the rate of turbulent kinetic dissipation.

Rate of kinetic Energy dissipation ε (5)

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_\epsilon})\frac{\partial \varepsilon}{\partial x_i}\right] + C_1\frac{\varepsilon}{K}(G_K) - C_2\rho\frac{\varepsilon^2}{K}$$

Where: σ_ε is the turbulent dissipation Prandalt number and C_1 , C_2 are the model constants.

$$\mu_t = \rho C_\mu \frac{K^2}{\varepsilon} \qquad (6)$$

Where: $C\mu$ is a model constants.

Energy Equation in fluid region (7)

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(u_i(\rho E + P)) = \frac{\partial}{\partial x_i}(k_{eff}\frac{\partial T}{\partial x_i} + u_j(\tau_{ij})_{eff}) + R$$

Where E and T are fluid energy and temperature, respectively. Also k_{eff} is the effective conductance coefficient of the fluid. The second term on the right hand side of equation 7 is due to the viscous effects, and R is due to the heat generation effects. It is worth noting that the radiation heat transfer is included in this term.

Energy Equation in Solid region

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{1}{r}\frac{\partial}{\partial r}(k_r r \frac{\partial T}{\partial r}) + k_z\frac{\partial^2 T}{\partial z^2} \qquad (8)$$

Where ρ is density, C_P is specific heat and k_r and k_z are the radial and axial conduction heat transfer coefficients, respectively. It is worth mentioning that when two different bodies are in contact, they touch each other at special points and there are some gaps between them in other points. Therefore, for steel coils, the axial thermal conduction coefficient k_z used in the calculations is taken from the standard textbook [15], while the radial thermal conduction coefficient is calculated from the following equation [16].

$$k_r = \frac{k_s}{\frac{1}{1+\frac{d_2}{d_{10}}}\left[1+\frac{\frac{k_s}{k_g}\times(2-\in)\times\frac{d_2}{d_{10}}}{\left[1+(\frac{k_s}{k_g}-1)\Delta\right]\times(2-\in)+(1-\Delta)\times4\times T_3^3\times d_2\times\frac{\in.\sigma}{k_g}}\right]} \qquad (9)$$

Where k_s and k_g are steel and gas conduction heat transfer coefficients, respectively. Δ is the ratio of the real contact area to the total area, and is about 0.13. d_2 is the gap between the steel layers and is normally about 20 μm, and d_{10} is the sheet metal thickness. $\in$ is the emissivity and its value is about 0.3, and σ is the Stefan-Boltzman coefficient.

Boundary Conditions

A simplified model of the whole system is shown in Figure 2. For this simple geometry, a fan boundary condition with a specified power is defined. For all solid walls, the no slip boundary condition is applied for momentum equation. The boundary condition for energy equation is not unique, i.e the thermal boundary condition for the inner side of the outer furnace is a constant temperature condition, while for other surfaces a combination of radiation and convection heat transfer are used.

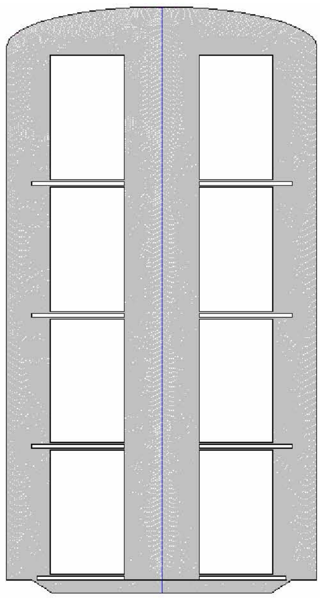

Fig. 2. Model of a box annealing with summetry line.

Due to the symmetry of the problem, only one half of the flow field is solved for 2-D case (see

Figure 2), while for a 3-D case, only one sixteenth of the geometry was enough. As the physical properties are temperature dependent, a 3rd order polynomial is employed to represent this temperature dependence.

Basic data

The circulating flow inside the chamber will transfer heat to the coils. The size of the chamber and the physical properties of both solid and fluid field are given in tables 1 to 4. Table 1 shows the fan head, gas mass flow rate, fan power, inner and outer diameter and height of the chamber. In table 2, all the convector dimensions are given .Table 3 represents the number and dimensions of the coils being heated inside the chamber. Table 4 shows the composition of the circulating HNX gas used inside the chamber.

Grid Study

As simulations were done in two different conditions i.e. a 2-D condition and a 3-D condition, two different grid studies in these two conditions are performed which will be explained in the following paragraphs.

2-D condition

The grid points used in this analysis are limited to the flow area. For the two-dimensional condition, triangular meshes are used (see Figure 3) while for the 3-D condition, hexahedral meshes are generated. The cells used near the walls were fine cells while coarse meshes were used away from the walls. In order to perform a grid independent solution, ten different meshes were used. The coarse mesh had 16000 cells while the fine mesh had about 135000 cells. The results of such a grid study are shown in Table 5. As it is shown in this table, the temperature of a particular monitoring points converges to a fixed value of 940.67 K when the number of grid point is about 100000. Therefore, if the number of the grid points is limited to about 100000, the results will be accurate enough and independent of the grid size.

3-D condition

The results of the grid study for 3-D condition are shown in Table 6. As it is shown in this table, eight different meshes were employed. The number of grid points used for this case was 980000 grid points for the coarse grid while 3900000 grid points were used for a fine mesh. Examination of table results indicates that in order to have a grid independent solution, the number of grid points should be about 3700000.

Table 1. specification of the inner chamber.

Fan head (mm H_2O)	Mass flow of Gas (m^3/hr)	Motor Power (kW)	Chamber inner diameter (mm)	Chamber outer diameter (mm)	Chamber Height (mm)
125	20000	22	2510	2520	4291

Table 2. Convector specification.

Convector thickness (mm)	Slot width (mm)	Ratio of real area to Total area	Number of slots	Convector diameter (mm)
10	25	58%	16	2020

Table 3. Coils specification.

Number of Coils	Thickness mm	Coil diameter mm	Coil height mm	Coil material
4	1	1600	1000	Steel

Table 4. Gas specification.

Gas inlet Temperature	Gas mixture
300K	$HNX = 0.9 \times N_2 \quad 0.1 \quad H_2$

Table 5. Grid study (2-D).

No. of cells	134966	123246	103631	91262	76923	68838	62133	37106	26747	16464
Temperature	940.67	940.81	940.99	941.32	943.77	946.62	966.26	979.04	996.68	1016.41

Table 6. Grid study (3-D).

No. of cells	3916822	3706324	3461386	2812138	2466312	1983791	1107268	981173
Temperature	941.66	941.71	942.37	948.07	960.92	981.12	979.04	1023.34

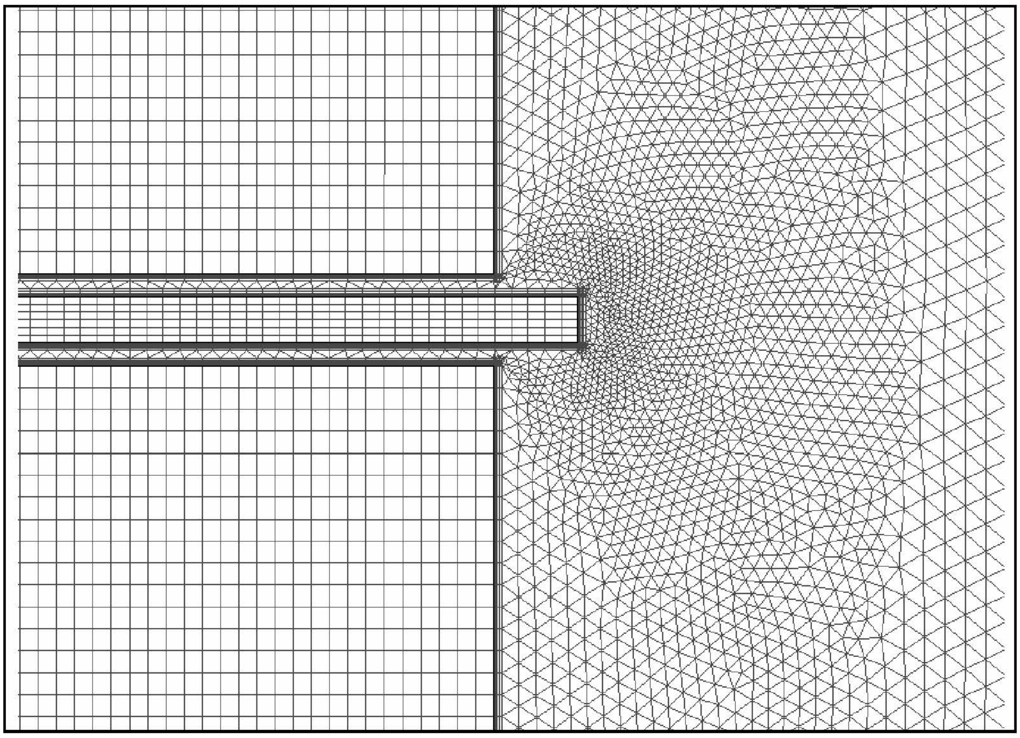

Fig. 3. A Sample of mesh for 2-D case.

Results

As mentioned earlier, the aim of this paper is to predict the temperature profile in the steel coils, in general and to find out the time variation of the temperature at the hot and cold spots, in particular. The position of the hot point is close to the outer top corner of a coil, while the position of the cold point is near the mid height of the coil in axial direction and at one third of the wall thickness (from inner face of the coil) in radial direction(see Figure 4). These two points are critical points; and by controlling their temperature, it is possible to control the temperature of the rest of the coil. It means if the temperature of the cold point reaches a certain value, the temperature of the rest of the points has to reach that value much before that. On the other hand, by preventing the hot point temperature from exceeding a certain value, it is possible to avoid a high temperature gradient between the hot and cold points in a coil, which will improve the quality of the product. In Figure 5, the temperature profile across the four coils used in a box annealing unit in a radial direction is shown and as it is seen, the coldest point corresponds to the coil number 1 while the hottest point corresponds to coil number 4. It is worth mentioning that coil number 1 is at the bottom of the chamber and the position of coil number 4 is at the top of the chamber. Therefore, we focus on the thermal behavior of the coldest point and plot the time variation of the temperature at the cold point of coil number 1. The calculated results for two different coil diameters at this point are shown in Figures 6 and 7. The field measurement results taken from Mobarakeh Steel Compound [17] are also shown in these figures and are denoted by astrisks. In these figures, the time variation of temperature for cold point of coil number 1 up to a temperature of 900°K is shown. As it is shown in these figures, agreement between the predicted and measured results is good and shows the program's ability to simulate the problem. It is worth mentioning that in annealing process, we normally try to bring the temperature of cold point to a value of 900°K and maintain it at that temperature for some time in order to perform the heat treatment needed. Having shown the program's ability, now we try to examine the effect of various parameters such as gas type used for annealing process, fan power, coil size, gas inlet temperature and geometry of the convectors. In the following paragraphs the effect of the aforementioned parameters on the performance of the annealing process is examined.

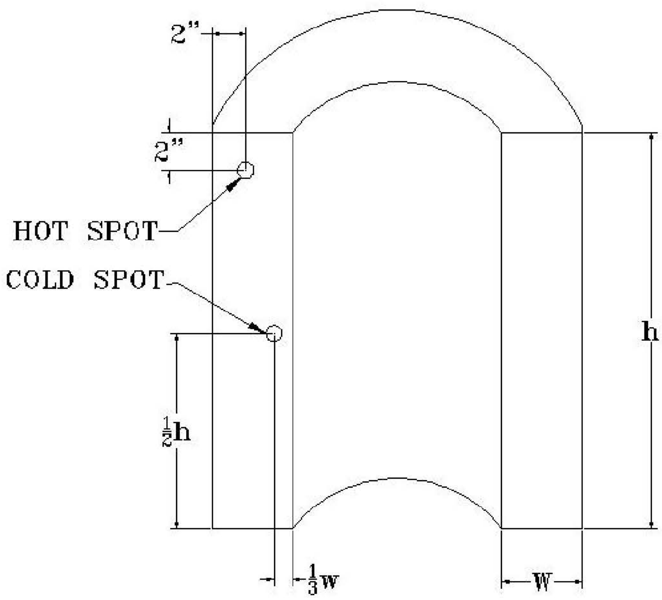

Fig. 4. Position of cold and hot spots in a coil.

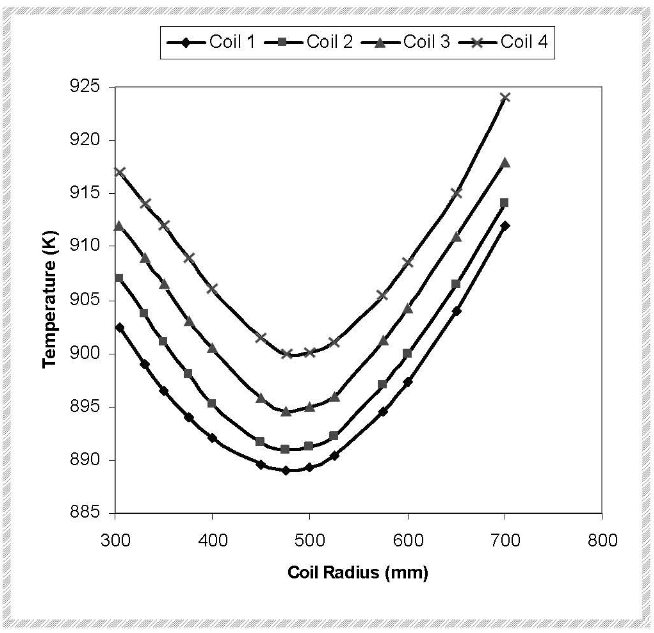

Fig. 5. Variation of temperature in radial direction for 4 coils(D=1400 mm).

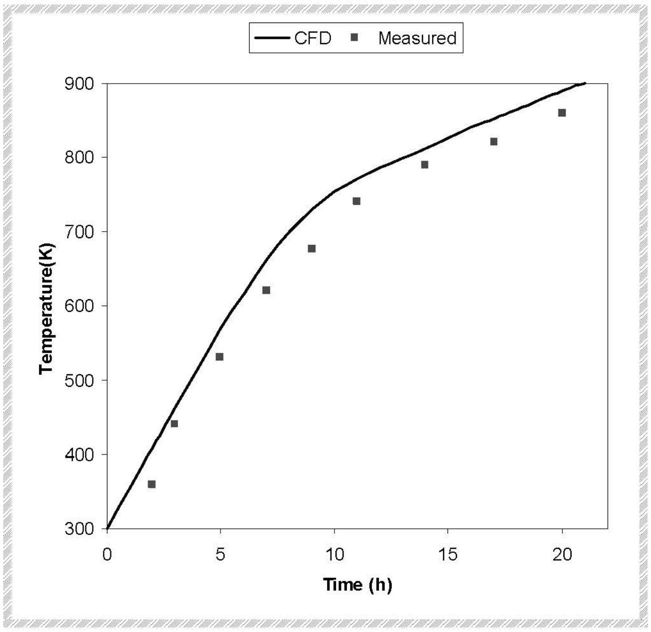

Fig. 6. Comparison of perdicted and measured results(D = 1400 mm).

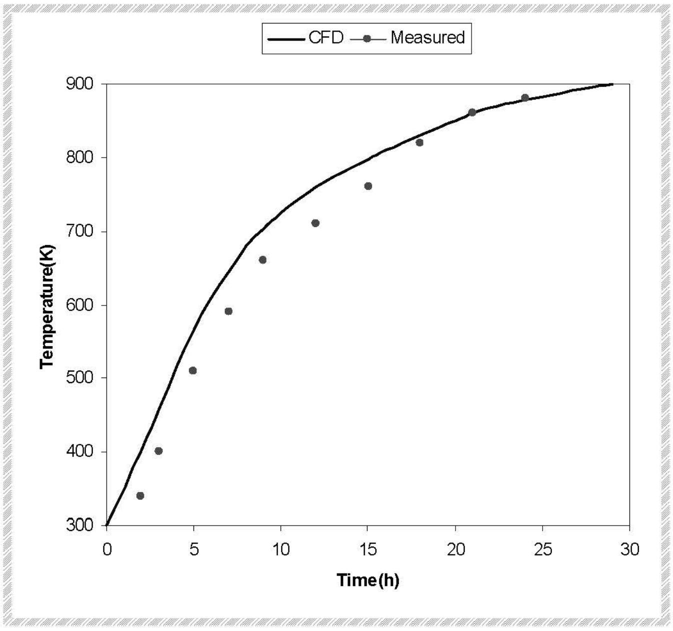

Fig. 7. Comparison of predicted and measured results (D = 1600 mm).

Gas type

As mentioned earlier, the gas used for annealing process is called HNX. HNX is a combination of hydrogen and nitrogen gases and is considered an almost inert gas (see Table 4).

As the thermal conduction coefficient of the hydrogen is higher than that of the nitrogen, the more the amount of hydrogen in the mixture, the better the thermal performance of the annealing process. Therefore, if we use a gas with 100% hydrogen, we will obtain the best performance. However, this requires a very high level of precaution to avoid danger of an unwanted explosion [13)]. In Figure 8, the annealing time for cold spot of coil number 1 to reach a temperature of 900 K using different gases is shown. As it is shown in this figure, this time for pure hydrogen is about 19 hours. If we use a gas with 60% hydrogen (HNX (60)) or a gas with 10% hydrogen (HNX (10)), the time to reach a temperature of 900 K will rise to 24 and 32 hours, respectively.

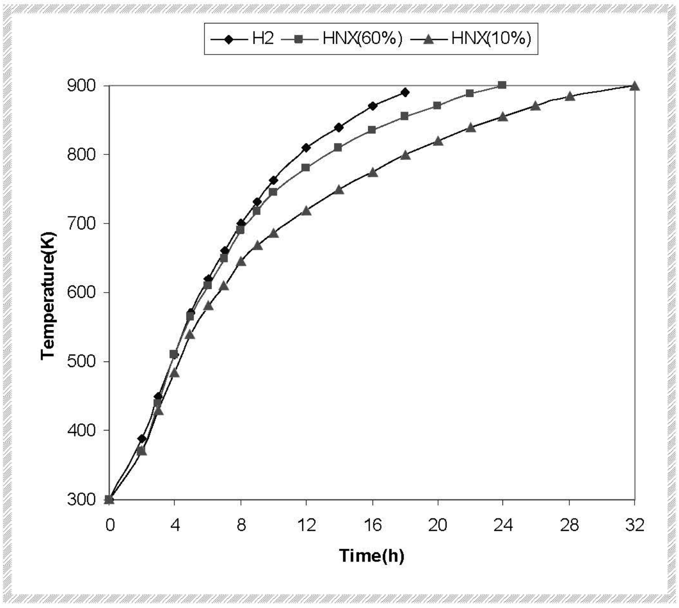

Fig. 8. Comparison of annealing time for various HNX gases.

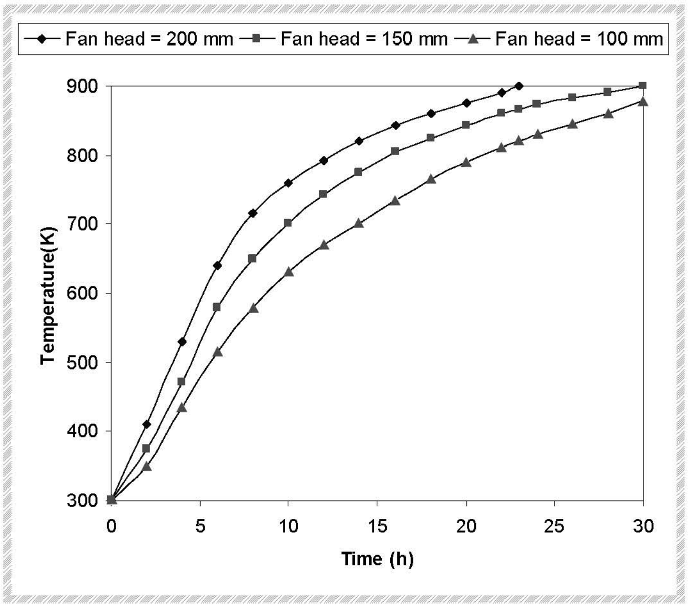

Fig. 9. Comparison of annealing time for various fan heads.

Fan Power

Any increase in fan power will increase the flow velocity and therefore the contribution of the convective heat transfer to the surface of the coils will increase. This effect will increase the temperature of the hot points.

The increase in the temperature at the hot points will raise the temperature gradient between the hot and cold points which will deteriorate the quality of the product. Therefore, the fan power should be limited to an acceptable level. In Figure 9, the time variation of temperature at the cold point of coil number 1 for various fan powers is shown. As it is presented in this figure, when the fan head (which is an indication of the fan power) changes from 100 millimeters of water to 200 millimeters of water, the time needed for the cold point of coil number 1 to reach a temperature of 900 K will be reduced from about 31 hours to about 23 hours. However, we should keep an eye on the temperature difference of the hot and cold points as well. Examination of Figures 10 and 11 will reveal this issue. As it is shown in Figure 10, the temperature difference between the hot and cold points after 16 hours is about 40 degrees. In this case the fan head is 125 millimeters of water. If the fan head is increased to 200 millimeters of water, the same temperature difference will rise to about 70 degrees. This is shown in Figure 11.

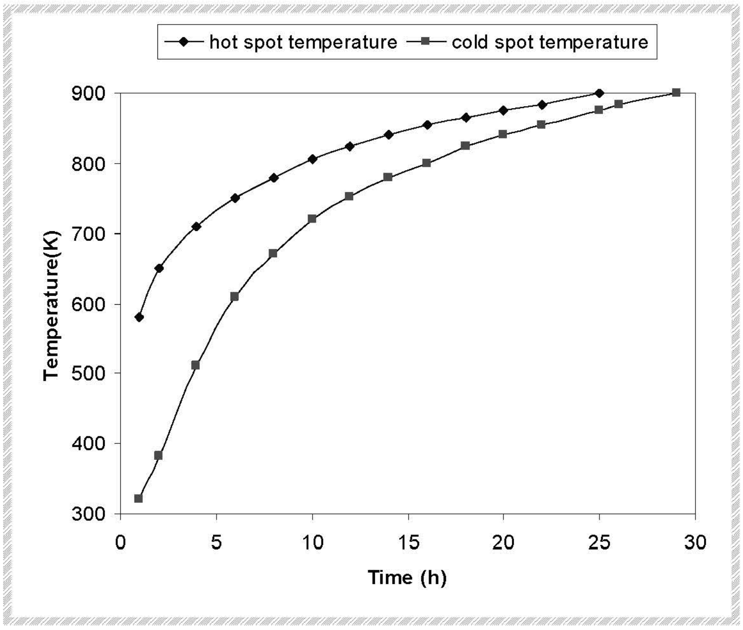

Fig. 10. Temperature difference for hot & cold spots (head =125 mm).

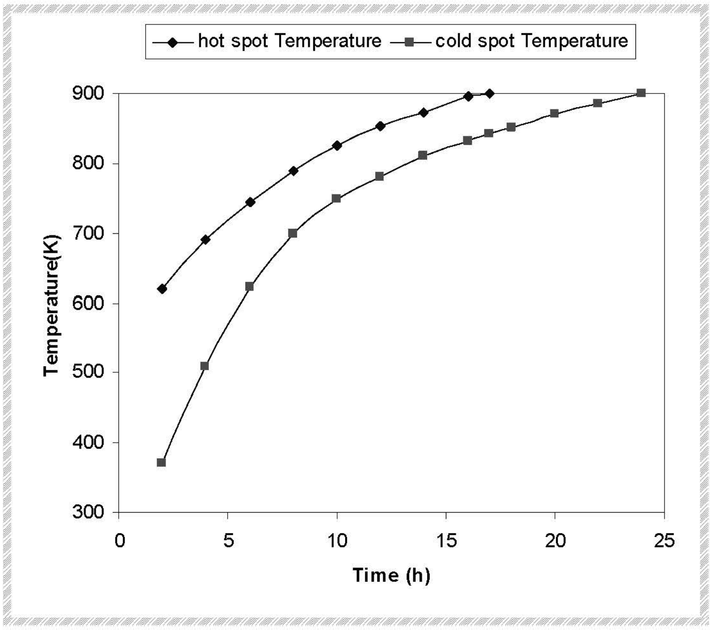

Fig. 11. Temperature difference for hot & cold spots (head =200 mm).

Inlet Gas Temperature

If the inlet temperature of the gas entering the chamber is changed, it will affect the performance of the heating process. In Figure 12, it is possible to see this effect clearly. As it is shown in this figure, by increasing the value of the inlet gas temperature, the time needed for the cold spot of coil number 1 to reach a temperature of 900°K would be shorter.

Coil Size

Figure 13 shows the annealing time for different coil diameters. As it is shown in this figure, if we reduce the coil diameter from 1800 mm to 1400 mm, the heating time will be reduced from about 40 hours to about 21 hours. Examination of Figure 14 shows that if we reduce the coil height, it is possible to obtain a similar result. However, it is worth mentioning that the thermal conductivity coefficient in the radial direction is much smaller than the same value in the axial direction. Therefore, if we reduce the coil size in the radial direction (i.e. reduce the coil diameter) instead of in axial direction (which means to reduce coil height), we will be able to obtain better results in terms of reducing the heating time.

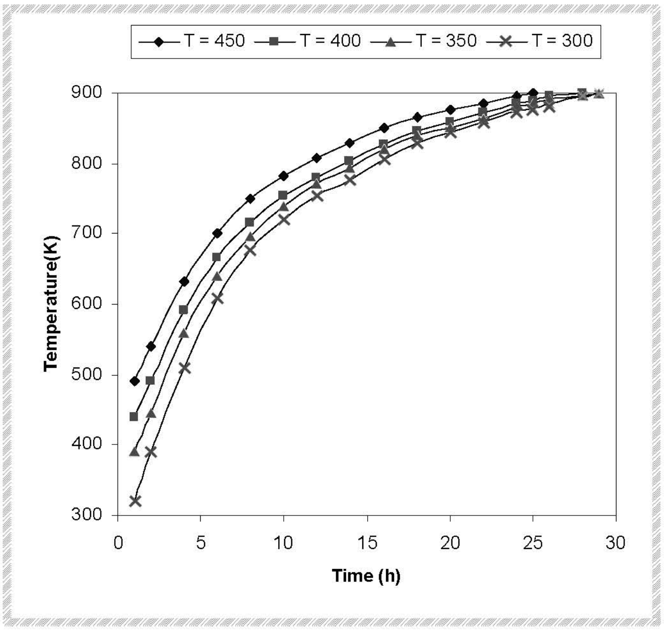

Fig. 12. Effect of inlet temperature.

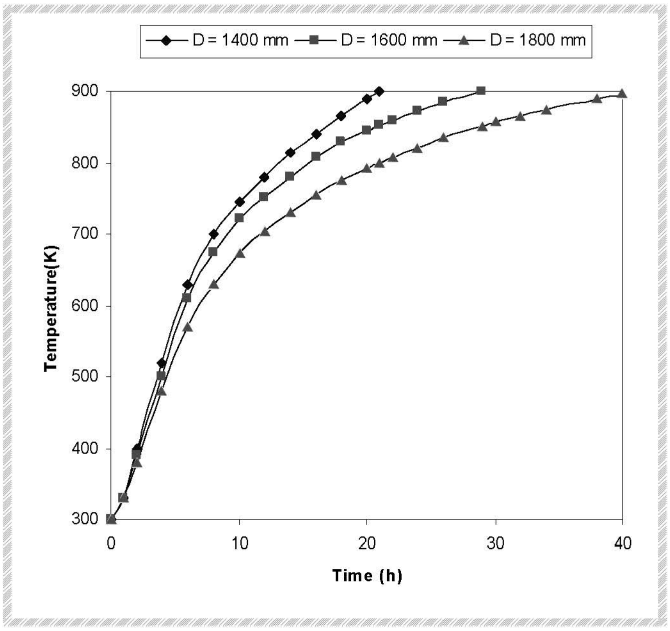

Fig. 13. Effect of coil diameter on annealing time.

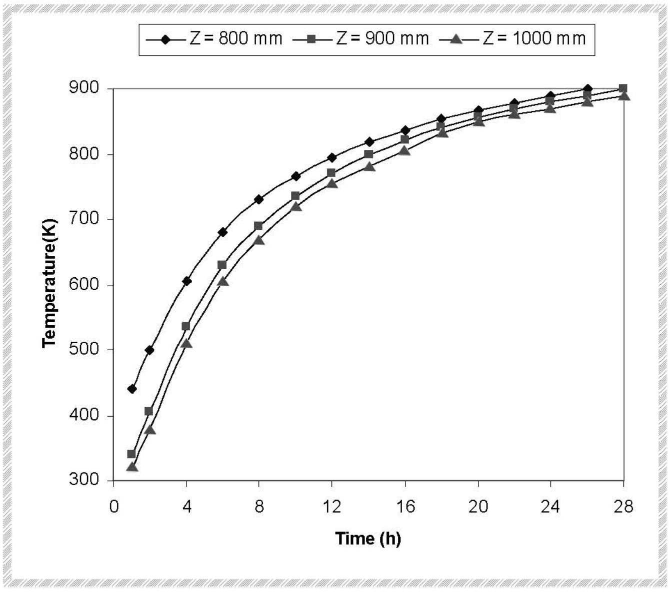

Fig. 14. Effect of coil height on annealing time

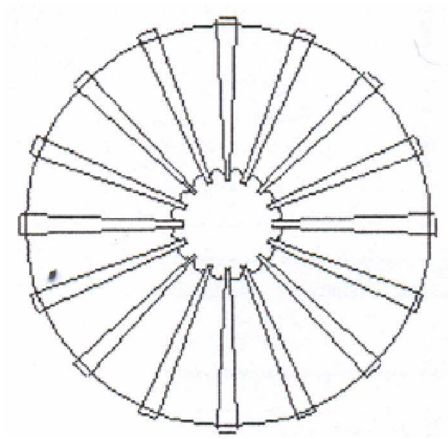

Fig. 15. A schematic view of a convector with spacers.

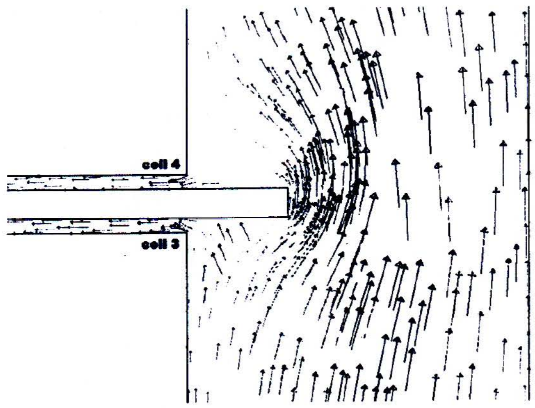

Fig. 16. Velocity vector plots around a convector between coils 3 and 4.

Convector Geometry

As mentioned earlier, convectors function is to separate the coils from each other and also to let the hot gas flow through them and heat the coils. Therefore, they are some sort of circular base plat with radial slots, and are located between the coils and allow the gas flow from outer side to inner side of the coils. Figure 15 shows a convector with its radial slots. To model a convector, we are not only facing the radial and axial directions, but also we have to consider the circumferential direction. It means that a complete 3-D model is needed which requires more effort and time. The convector geometry should have such a shape that it allows more flow from its top and bottom. As the thermal conduction coefficient in Z direction is more than the thermal conduction coefficient in R direction, more flow will lead to more surface heating and it will improve the quality of the product. In Figure 16, the flow field around one of the convectors is shown. However, to investigate the effect of the convector geometry, three different parameters are considered. These parameters are convector thickness, convector diameter and convector slot size. In the following paragraphs these parameters are treated.

Convector Thickness

Regarding the convector thickness, it should be realized that if the convector thickness is increased, more flow passes through them which will lead to a better heat transfer. On the other, hand if the pumping flow rate is fixed, increasing the convector thickness will lead to less flow velocity; and therefore, the heat transfer will be reduced. Apart from the effect of velocity on the heat transfer, the effect of the flow velocity on the friction loss should also be taken into account. At a constant mass flow rate, if the convector thickness is reduced, the flow velocity will increase, leading to an increased friction loss. In Figure 17, the effect of convector thickness on the annealing time is shown. As it is shown in this figure, the results for three different thicknesses of 10, 30 and 40 mm are shown. As the results show, the thickness of 30 mm is much better than the other two.

Convector Diameter

By increasing the convector diameter, the time needed for cold point of the coil number 1 to reach a temperature of 900 K will be reduced. However, it is not possible to increase the convector diameter too much. If this diameter increases too much, it will force most of the flow to pass through the gap between the coils numbered 1 and 2; and therefore, the coils numbered 3 and 4 will receive less flow, which will reduce their heat treatment capability and therefore, will increase the annealing time.

Hence, there is an optimum diameter for convectors. In Figure 18, the effect of convector diameter on the annealing time is shown. Examination of the results show when the convector diameter changes from 1600 mm to 2010 mm, the annealing time is reduced up to 6 hours. There is no need to mention that the coil diameter is again 1600 mm in this case.

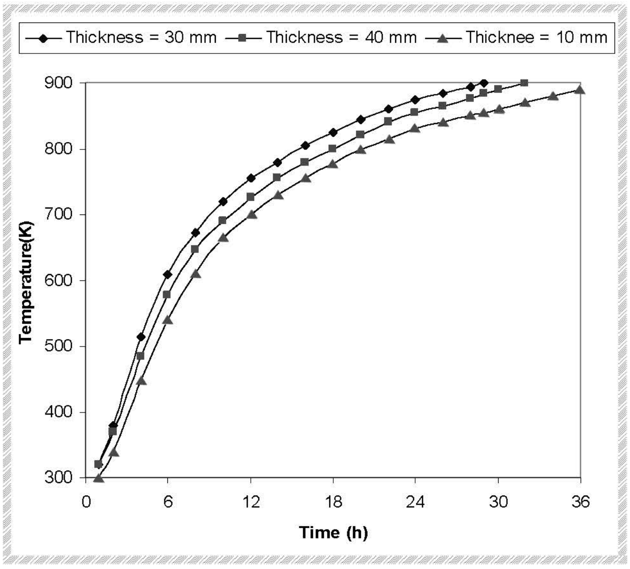

Fig. 17. Effect of convector thickness on annealing time.

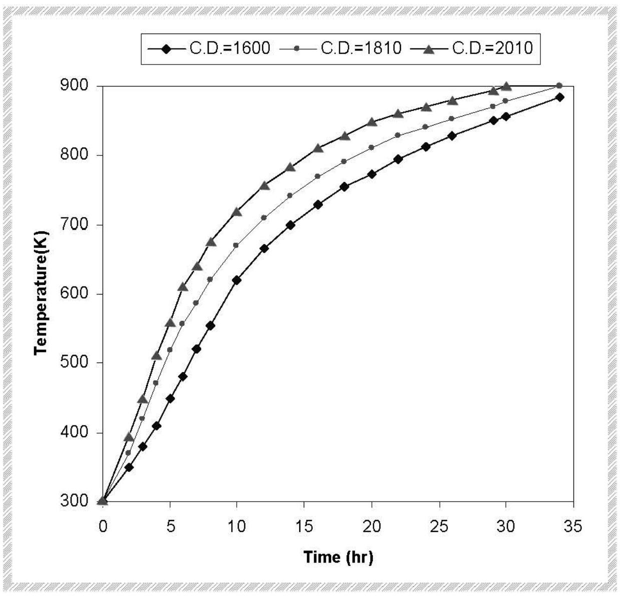

Fig. 18. Effect of convector diameter on annealing time.

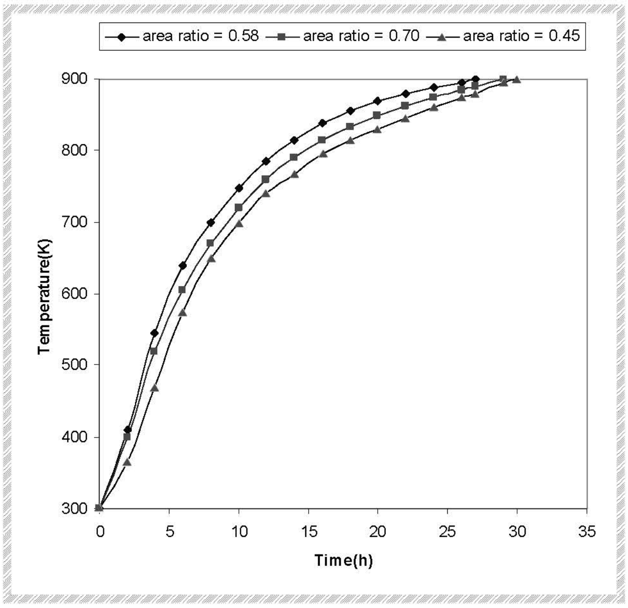

Fig. 19. Effect of spacer area on annealing time.

Convector slot size

When using the convector, the goal is to increase both flow area and flow velocity. It is clear that these two effects are working in opposite directions. It means that if the slot sizes on the convectors are decreased, the flow area will be reduced and the flow velocity will increase and vice versa. Therefore, in order to reach an optimum slot size, more investigations are needed. Hence, the ratio of slot area (real flow area) to the total area is considered as a parameter and its effects are studied. In Figure 19, the effect of this parameter on the annealing time for three different cases is shown. As shown in this figure, the annealing time for three different area ratios of 45, 58 and 70% are plotted. Examination of these results show that the area ratio of 58% is the optimum value. This optimum area ratio well agrees with the existing figures in the Mobarake Steel Compan[17].

Conclusion

Box annealing is a very useful method to improve the quality of a cold rolled steel coil. Since it is a huge energy consuming process, great care is required to reduce the amount of consumed energy. A thorough numerical study is able to show all the possible potentials available to the operator of a box annealing unit in order to reduce energy consumption. There are a number of various parameters affecting this matter. Among the various parameters affecting the energy saving it is possible to mention the coils diameter, the coils height, the type of the gas used for heating process, gas inlet temperature, the circulating fans power, etc. The potentials existing for each case have been shown and the drawbacks are also considered too.

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Nomenclature

c_1, c_2, c_μ	Turbulence model constants
C_p	Specific heat
d_2, d_{10}	Inner layer thickness, sheet metal thickness
E	Energy
Fi	Body force
K	Turbulent kinetic energy
k_{eff} , k_r, k_z	Effective, Radial and axial conduction coefficient
k_g, k_s	Gas and Steel conduction coefficients
u,v,w	Velocity components
x,y ,z	Direction coordinates
G_k	Turbulent kinetic energy generation
P	Static pressure
T	Temperature
ε	Turbulent energy dissipation
$\in$	emissivity
ρ	Density
μ	Viscosity
σ_k	Turbulent kinetic Prandalt number
σ_ε	Turbulent dissipation Prandalt number
σ	Stefan-Boltzman Constant
Δ	Ratio of real area to total area