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Simplex Enhanced Numerical Modeling of the Temperature Distribution in a Hydrogen Cooled Steel Coil Annealing Process

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Abstract

The temperature distribution of steel coils during annealing process in hydrogen has a significant effect on their quality. It is approached by numerical modelling using the differential equations governing the heat transfers involved. The resolution is performed by the method of finite differences. Convergence standards of different numerical algorithms are adjusted on the basis of a compromise between precision and time by the method of experimental plan. Thermal coefficients used in the model are also adjusted by the simplex optimization technique. Modeling results show good agreement with experimental measurements.

*Keywords:*steel; coil; hydrogen annealing furnace; method of finite differences; designs of experiments; simplex; modeling

1. Introduction

Steel coils are annealed to reduce the internal strain of cold working or to improve machinability byfacilitating recovery and recrystallization at elevated temperatures (Fig. 1). The time and temperature influence on these metallurgical reactions has been well documented for years. Several calculation models are available in the literature to tackle the general problem of heat transfer in furnaces for heat treatment [1-4]. During this study the temperature distribution in a coil will be governed by the heat equation in cylindrical coordinates solved by finite differences [5].

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Nomenclature

(r, z)	Cylindrical coordinates, m
T	Temperature, K
c_p	Specific heat, J $kg^{-1}K^{-1}$
ρ	Density, kg/m^3
k	Thermal conductivity, W $m^{-1}K^{-1}$
h	Heat transfer coefficient, W $m^{-2}K^{-1}$
φ_{radi}	Radiative flux, W/m^2
φ_{conv}	Convective flux, W/m^2
ε	Emissivity
α_L	Coefficient of coil expansion, K^{-1}
h_o	Interstice between two windings, m

The numerical and thermal coefficients used in the model are determined with optimization technique of simplex [6,7].

2. Physical description

In many batch annealing furnace designs, annealing is carried out for several coils stacked one above the other forming a single pile as shown in figure 1. The format of coils in a base is variable and depends on the desired future use. The height usually varies from 500 to 1400 mm, inner diameter from 500 to 600 mm, outer diameter from 1200 to 2200 mm and thickness from 0.3 to 3 mm. Therefore the number of coils in the annealing base varies from 3 to 6, they are separated by convectors.

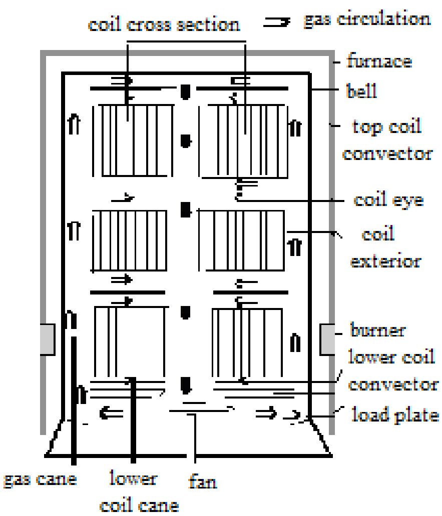

Fig. 1. Batch annealing furnace design

The stack is capped by a bell in which circulates a protection gas (hydrogen) to avoid any phenomenon of oxidation during annealing operations. A furnace consisting of 6 burners facing the first coil fits over the entire load and ensures gradual heating. The burners use natural gas and are set to deliver a fixed amount of heat (600 kW) when furnace nozzles are at their maximum apertures. To avoid problems of oxidation, the annealing base is swept by a reducing gas with respect to oxygen (4 to 5 m^3/s). For security reasons, the plant uses 2 protective gases: nitrogen (with 5% hydrogen) and pure hydrogen. The circulation of protective gas is assured by a centrifugal fan.

3. Analysis and modeling

3.1 Heat transfer equations

The conduction problem inside the coil can be treated by a following equation

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_r r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) \quad (1)$$

The following assumptions are used:
- Symmetrical temperatures: Any point belonging to the perimeter of a circle centered on the axis of revolution of the coil is at the same temperature.
- Anisotropic body: Conductivity is not isotropic because the coil cannot be taken as a homogeneous solid cylinder. When the heat penetrates in the radial direction, the flux encounters a succession of gaseous interstices which will change the conductivity.
By orthotropy:

$$\varphi_r = -k_r \frac{\partial T}{\partial r} \; ; \varphi_z = -k_z \frac{\partial T}{\partial z} \quad (2)$$

- The initial temperature distribution $T(r, z)$at $t = 0$ is the temperature of the coil after cold rolling (70°C).
- Radiative and convective fluxes are introduced as boundary conditions: (Eq.3) and (Eq.4).

- Radiative flux:

$$\varphi_{radi}^{North} = \varphi_{radi}^{South} = \varphi_{radi}^{West} = 0 \;\; ; \varphi_{radi}^{East} \neq 0 \quad (3)$$

- Convective flux:

$$\varphi_{conv} = h(T_{co} - T_g) \quad (4)$$

Where: T_{co} is the coil temperature, T_g is the hydrogen gas temperature.

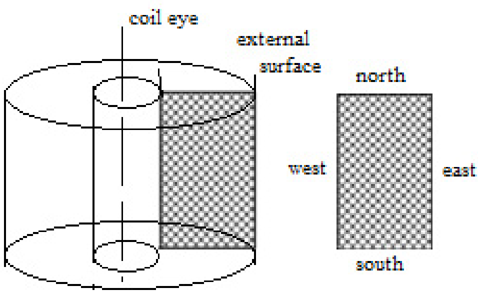

Fig. 2. Integration area for PDE heat transfer computation in cylindrical coordinates

Equation (1) is numerically solved by a finite differences method with accelerating convergence [5,8,9].

3.2 Thermal model calibration

Some thermo physical parameters of the thermal model are perfectly determined (c_p, ρ, k…), others are only known approximately, because they are determined experimentally with quite pronounced uncertainties (h , ε, α_L ...).
In order to adopt suitable coefficients, the results of temperature measurements are compared to the results provided by the thermal model; calibration is performed by the simplex method.

3.2.1 The simplex method

This method allows to optimize the values of the temperature coefficients of our model by making optimal its response. An optimization of this type is often carried out by varying a single coefficient at a time. But, this method is completely ineffective in the case of our model because the thermal coefficients are all interdependent.

- *Illustration of the method used*

As a matter of fact, let us consider the example of the heat flux entering the outer face of the coil (Fig. 3):

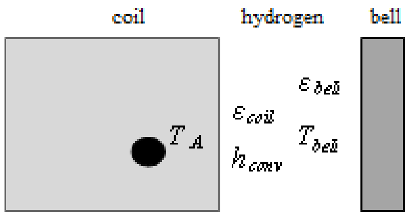

Fig.3. Thermal coefficients used for temperature optimization

We want to attain a temperature $T_A$at point A of the coil. If ε_{coil}; ε_{bell}; h_{conv} or T_{bell} increase then T_A increases. It is obvious that we can optimize our temperature at point Aonly by the variation of one of the above mentioned parameters. Therefore we must use a method that allows finding the right values for these coefficients through their simultaneous variation.
In numerous cases, the optimization is done by numerical methods to optimize a functional (conjugate gradient, Kuhn's, Powel's algorithm ...); but these methods assume that the function to optimize is known.
In our case, the function is not known (it is the difference between the measured and modelled temperatures at certain points of the annealing base).Therefore we should use a particular optimization method: the simplex method.(This method has no connection with the simplex method due to George Dantzig).
This optimization method was proposed by Spendey and Himsworth in 1962 [10]. It is a geometric shape of dimension K where K represents the number of coefficients of the model (K = 11, Table 1.a). These points are equidistant from a central point and distributed uniformly over a hyper-sphere of dimension K.
For $K = 2$, we obtain a triangle presented by figure4:

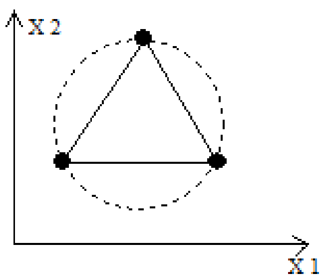

Fig. 4.Geometric representation of simplex

- The basic principle consists to evolve this shape towards the desired optimum by eliminating the worst response of one of simplex points.
- The simplex method consists in using appropriate matrix transformations to move towards the sought optimum by choosing a diametrically opposite direction from the point making the function to optimize the most unfavourable.

- The edges of the simplex are set to an initial value and we move towards the optimum with this step.
- Once the optimum achieved with the fixed step (simplex loops on itself), then we can reduce its step of progression until the desired accuracy is achieved.

- *Function to minimize*

This is to minimize the differences between the experimental and modelled temperatures at certain points of the annealing base, by adjusting at best the thermal coefficients.

It would determine the parameters *P* that minimize the functional *S (P)*:

$$S(P) = \min[\frac{1}{r}\sum_{k=1}^{r}\frac{1}{n_r}\sum_{i=1}^{n_r}\frac{1}{\tau^r}\sum_{j=0}^{\tau^r}(\overline{T_{n,jdt}^{r}} - T_{n,jdt}^{r})^2 \quad (5)$$

Where:
r : Number of annealing
n_r: Number of measuring points in the annealing base
$\overline{T_{n,jdt}^{r}}$: Experimental temperature measurement at a point *n* of *r* annealing at time *t*
$T_{n,jdt}^{r}$: The simulated temperature by the model at a point *n* of *r* annealing at time *t*
τ^r: The number of time steps of annealing *r* and *dt*: time between 2 experimental measurements.

4. Results and discussion

4.1 Results

Let's make the initial simplex table containing the coordinates of the starting point, the minimum and maximum values for these coordinates and the simplex evolution step (Table 1.a).
In order to analyze the evolution of the simplex, we consider a measuring point temperature: $n_r = 1$.

Table 1a Calibration parameters of the thermal model before optimization

Variables	Value	Minimum	Maximum	Step
$factor\ of\ conduction\ k_{bell}$	0.9	0.05	1.2	0.1
$factor\ of\ convection\ h_{lowercoil}$	1.5	0.5	3	0.1
$correction\ factor\ of\ h_{highcoil}$	1.5	0.5	2	0.1
$correction\ factor\ of\ h_{spacer}$	1.5	0.5	2	0.1
$correction\ factor\ of\ h_{bell}$	1.5	0.5	2	0.1
α_L	5.10^{-5}	1.10^{-5}	6.10^{-5}	$2.5.10^{-6}$
h_0	3.10^{-5}	1.10^{-6}	6.10^{-5}	$2.5.10^{-6}$
ε_{coil}	0.45	0.2	0.7	0.05
ε_{bell}	0.7	0.5	0.95	0.05
$correction\ factor\ of\ h_{eye}$	1	0.5	2	0.1
$correction\ factor\ of\ h_{gascane}$	1	0.5	2	0.1

The value of the function S (P) is 1663.
The influence of the minimization on the temperature distribution is shown on the graph representing the evolution of the temperature at the heart of the lower coil of the stack before charging using the simplex method (Fig 5a).

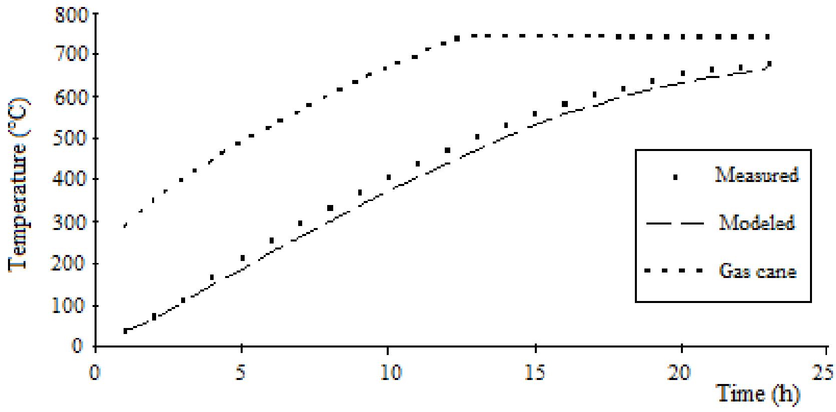

Fig.5a. Temperature at the heart of the lower coil of the stack before charging using the simplex method

Simplex provides a response for the temperatures to plus or minus 30 K without a preliminary calibration of the coefficients.

Amid the simplex iterations, we get the answer 897 (Table 1.b)

Table 1b Calibration parameters before change of step

Variables	Value	Step
$factor\ of\ conduction\ k_{bell}$	0.58	0.1
$factor\ of\ convection\ h_{lowercoil}$	1.52	0.1
$correction\ factor\ of\ h_{highcoil}$	1.59	0.1
$correction\ factor\ of\ h_{spacer}$	1.75	0.1
$correction\ factor\ of\ \ h_{bell}$	0.99	0.1
α_L	$4{,}13.10^{-5}$	$2.5.10^{-6}$
h_0	$3{,}10.10^{-5}$	$2.5.10^{-6}$
ε_{coil}	0.49	0.05
ε_{bell}	0.80	0.05
$correction\ factor\ of\ h_{eye}$	1	0.1
$correction\ factor\ of\ h_{gascane}$	1,24	0.1

Once the optimum is reached with the preset step, the latter is decreased to yield 385 at the end of iteration (Table 1.c, Fig 5b).

Table 1c Calibration parameters before change of step

Variables	Value	Step
$factor\ of\ conduction\ k_{bell}$	0.16	0.025
$factor\ of\ convection\ h_{lowercoil}$	2.87	0.025
$correction\ factor\ of\ h_{highcoil}$	1.99	0.025
$correction\ factor\ of\ h_{spacer}$	1.60	0.025
$correction\ factor\ of\ h_{bell}$	1.21	0.025
α_L	$4{,}56.10^{-5}$	6.10^{-7}
h_0	$2{,}8.10^{-6}$	6.10^{-7}
ε_{coil}	0.67	0.0125
ε_{bell}	0.92	0.0125
$correction\ factor\ of\ h_{eye}$	1.39	0.025
$correction\ factor\ of\ h_{gascane}$	0.81	0.025

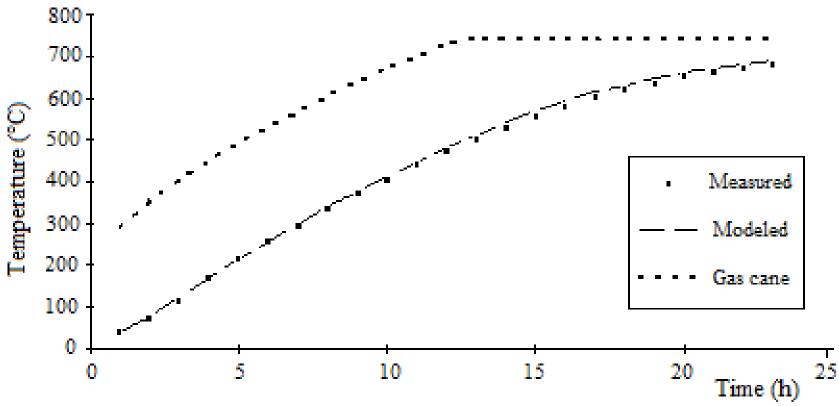

Fig. 5b. Temperature at the heart of the bottom of the stack coil after calibration by the simplex method

Simplex provides a response for the temperatures to plus or minus 8K after calibration by the simplex method.

4.2 Discussion

The emissivity of the bell 0.92 obtained is similar to that of steel having lampblack on its surface.
The convection coefficients are consistent with those provided by the literature [11], with the exception of the upper coil subjected to the radiation of the bell and the bottom of the stack, rather high values due to the variation in duct section.
The coefficient convection at the bottom of the stack is virtually multiplied by a factor 2.9. Indeed, studies by Kays [12] show that as the channel widens and leaves the square duct structure to move towards a rectangular duct, the more increase in the Nusselt number and consequently the convection coefficient also increases. In the case of the stack bottom, Kays shows that the convection factor should be 40% higher for the lower part of the stack than that for the intermediate convector.
As for the expansion coefficient of the coil, the resulting value is similar to the linear expansion coefficient of steel.
The most significant result of this optimization method is that simplex never reached, during all iterations, the boundaries of validity that we fixed (except in the case of the convector at the stack top). Since all factors are interdependent with each other, just the fact of finding the correct emissivities implies that the other factors may not

be tainted with excessive errors.
Indeed, suppose that we take an excessively high value for the convection coefficient in the outer turns of the coil, then the simplex, minimizing the function will lower the emissivity of the wall to ensure an adequate heat flux on the surface of the coil. Then we might get a very low emissivity. Well, these emissivities are consistent with the usual values accepted in the literature. We can conclude that our model is right and that all assumptions are correct.

5. Conclusion

This work has highlighted the importance of the optimization simplex method. Thermal calibration allowed the determination of the thermo-physical parameters of the model. Emissivity obtained is compatible with the usual values accepted in the literature.
Modeling results show good agreement with experimental measurements, thus showing the great potential of the model as a tool for the determination of the temperature distribution during an annealing process under hydrogen gas.

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