UTILIZATION OF INDIRECT MEASUREMENT IN THE ANNEALING PROCESS OF THE STEEL COILS

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Abstract
The estimation of suitable mode of the steel heating is the problem that is also met at annealing of the steel coils. Temperatures inside annealed coil of the steel coils are unknown because it is not possible to measure continually and directly (destruction of the batch, possible defect of the sensor at manipulation with the batch etc.). The missing information about temperature behaviour inside a steel coil can lead to the extension of annealing duration (increasing the energy cost), shortening the annealing duration (poor quality of annealed batch). Presented problems at temperatures estimation in the steel coils help to solve so-called „System of indirect temperature measurement" (SITM). This system is based on direct measurement of the atmosphere temperature in the furnace space between safety cover (bell) and the coil. SITM calculates temperature field inside the coil continually at the time based on continually measurement of the atmosphere temperature T_A.

Keywords: annealing, indirect measurement, steel coil, mathematical model

1 Introduction

With the gradual implementation of automation into industrial practice is needed a considerable attention to the accuracy of measurement of variable process [1-3]. Above all it had and has a great effect on possibilities of the control process that is closely associated with a quality of produced products.

Basis of the modern industry operations is automated monitoring system for monitoring and recording the process values. Shortness the most monitoring system is inability to monitor process variables that are not directly measurable but they estimate qualitative parameters of the process. For this reason it is also needed to include models of indirect measurement into monitoring system [4, 5].

At the material processing there is a very important process of variable temperature processed material respectively batch from various reasons we cannot continually measure. Among the main reasons belong following:

- aggressiveness and high atmosphere temperature where process runs,
- batch movement,
- space restrictions for sensors placement,
- change of the batch, semi-product and volume properties.

For this reason another temperature is measured e.g. spent gases temperature. By this temperature there is a process regulated decrease production quality. For this reason it is needed to develop new methods and models for indirect measurement of the process variables [6-9].
Even if some methods of indirect measurement are known and verified its application is not possible for all processes without its adaptation and verification. Verification of these or new methods based on direct measurement at industrial conditions are often unrealized. It is appropriate to have available complex simulation model of the given process. Input to the simulation model can be also indirect measured process variable with outputs from the model of indirect measurement. By junction of model for indirect measurement with a complex process model we can decrease uncertainty about process behaviour [10, 11].
Decreased uncertainty (increased information) about the process enables to use more methods and control algorithms. In addition there is possible control process based on relevant indirect measured variable control that has been non-measurable yet and replaced by another non-relevant variable.

2 Material and experimental methods

Task of indirect temperature measurement system in the massive batch (coil) is to indirect measure temperatures inside the batch during its heating process. There was chosen steel coils annealing process. The massive batch in the annealing process represents steel coil. For verification of SITM was performed control measurement. At selection of this control measurements were regarded various annealing modes, steel quality, diameters of coils and various thickness of the steel sheet with goal of the widest verification of the SIMT. The diameter of coils was in interval 1500-2200 mm with thickness of the steel sheet in interval 0.6-1.5 mm.
System rises from one continually measured value namely atmosphere temperature (T_A). This system provides information about temperatures inside annealed batch based on temperature T_A (**Fig. 1**). Present SITM consists of two subsystems that are interworked:

1. subsystem for indirect measurement of surface temperatures (SIMST) of the batch,
2. subsystem for indirect measurement of inner temperatures (SIMIT) of the batch.

Both subsystems are very important in the complex system if indirect temperature measurement. The inner temperatures of massive batch are calculated by the method of elementary balances based on surface temperatures. Seeing that surface temperatures are not measurable directly, was necessary to prepare model (models) for indirect measurement of this temperatures [6, 10].

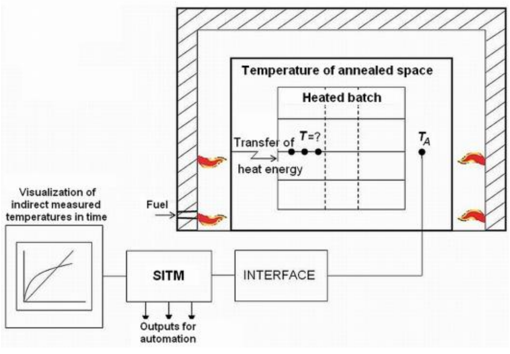

Fig.1 Principle of SITM measurement

2.1 Indirect measurement of surface temperatures

The models for indirect measurement of the surface temperatures are created from differential equations, which task is to indirect measure surface temperatures based on direct measured safety atmosphere temperature. General form of equation for calculation of surface temperature depending on atmosphere temperature is following:

$$Tp_i[k] = \bar{b} \cdot T_A[k], \qquad i=1,\ 2,\ ...,\ n \tag{1}$$

where Tp_i – i-th surface temperature of the coil, $\bar{b}$ – vector of differential equation coefficients (parameters), T_A – temperature of protective atmosphere of the furnace space, k – time step, n – count of the surface temperatures.

For verification this method were proposed several variants of the models. Its single input is atmosphere temperature in a various forms (T_A, T_A^2, T_A^{-1}). In next variants there were models extended with the next parameter that was Fourier´s non-dimensional criterion [12].
In the first stage there was created self-model for each surface temperature (Tp_i). Disadvantage of this method is the state when a destruction of thermocouple for surface temperature measurement during checking measurement occurs. Then it is not possible to determine parameters of the model ($\bar{b}$) for this concrete surface temperature. From this reason the second variant was designed so that the created three models of the surface temperatures for each coil. One model for surface temperatures on outer side of the coil, the second for surface temperatures placed in the middle of the coil and the third model for surface temperatures placed on inner side of the coil. From this reason models were extended at highness of the surface temperature placement above stand (v_{term}).
Regarding presented facts the proposed model for indirect surface temperatures has following form and structure:

$$Tp_i[k+1] = b_0 + b_1 \cdot T_A[k+1] + b_2 \cdot T_A^2[k+1] + b_3 \cdot T_A[k] + b_4 \cdot T_A^2[k] + b_5 \cdot v_{termi} \cdot Fo[k+1] \tag{2}$$

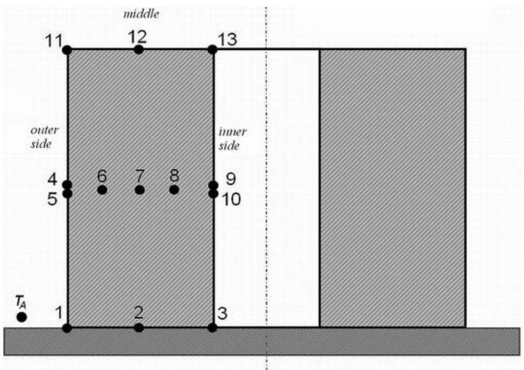

Fig.2 Measurement places for surface and inner temperature at preventive measurement

The verification of presented model for surface temperature calculation was performed on measured data from preventive measurement. On **Fig. 2** at cut of the coil is shown measurement placed of surface temperatures, of the inner temperatures and atmosphere temperatures (T_A) at control measurement. For verification of SIMIT was direct measured 10 surface temperatures - 4 on outer side of the coil (T_1, T_4, T_5, T_{11}) , 4 on the inner side of the coil (T_3, T_9, T_{10}, T_{13}) and 2 in the middle of the coil (T_2, T_{12}).

2.2 Indirect measurement of inner temperatures

Task of the SIMIT is from indirect surface temperatures (Tp_i) obtained with SIMST to indirect measure temperature at inner of the batch (coil) T_{Vi}.

SIMIT is based on elementary balances method that rises from dividing the batch (coil) on elementary cuboids (**Fig. 3**) in direction of axis x and axis y, where at the centre of each cuboid (node point) is centred temperature. Elementary balances method is in SIMIT expressed for boundary conditions of the first type where temperatures on coil's surface are known and unknown is temperature at inner of the batch [13, 14].

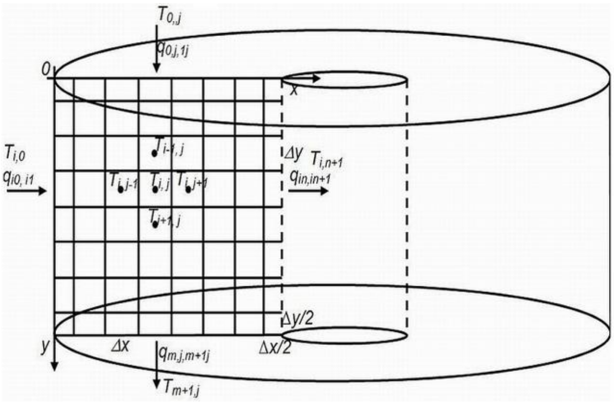

Fig.3 Partition of the coil into elementary cuboids

Seeing that the batch is anisotropy (unequal size of the gaps between single spire), method was adjusted so that it was possible to determine heat conductivity in direction of the axis x. In direction of axis y were used values of heat conductivity based on chemical composition of the annealed coil [15, 16].

Heat radial conductivity defined at condition of the steel coil conductivity can be effective in a solving model, infilling gas and its abundance ratio with utilization of the following equation:

$$\lambda_u = \frac{d_s + d_g}{\dfrac{d_s}{\lambda_o} + \dfrac{d_g}{\lambda_p}} \tag{3}$$

where λ_u – heat conductivity of the steel layer and gas [W·m^{-1}·K^{-1}], λ_o – heat conductivity of the steel [W·m^{-1}·K^{-1}], λ_p – heat conductivity of infilling gas [W·m^{-1}·K^{-1}], d_s – average thickness of the steel coil´s sheet [m], d_g – average thickness of the gap in the coil [m].

For calculation of inner temperatures with the elementary balances method is needed to estimate time step of the computation from the term of stability (4) [17].

$$\Delta\tau_S \le \min \frac{c \cdot \rho}{2 \cdot \lambda \cdot \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right)} \tag{4}$$

where λ – heat conductivity of annealed coil [W·m^{-1}·K^{-1}], c – heat capacity of annealed coil [J·kg^{-1}·K^{-1}], ρ – density of annealed coil [W·m^{-1}·K^{-1}], Δx – dimension of the elementary cuboid in direction of the axis x [m], Δy – dimension of the elementary cuboid in direction of the axis y [m].

2.3 Algorithm SITM at directly measured temperature of the atmosphere

After the verification of the both subsystems (SITM and SIMIT) of indirect temperature measurement on a preventive measurement and its relative interconnection was proposed algorithm that from direct measured temperature of the atmosphere continually and indirectly measures temperatures at inner of the annealed coil.

In SITM at directly measured temperature of atmosphere are values of temperatures at fulfilment of the term of stability (4) between two continually time period estimated from linear approximation [18-20].

The algorithm of indirect measurement of direct measured temperature of the atmosphere between two time steps (realized by direct measurement) temperature of the atmosphere (τ - previous measurement time; $(\tau+\Delta\tau)$ – actual measurement time; p – count of the coils; h – index of the coil; m_h – count of the inner points in heat array in direction of the axis y at h-th coil; n_h – count of the inner points in a heat array in direction of the axis x at h-th coil; i, j – indexes of temperatures in h-th coil responds heat array; T_A^{τ} – atmosphere temperature in time $(\tau+\Delta\tau)$; $\Delta\tau$ - period between two realized measurement of the atmosphere temperature T_A^{τ} and $T_A^{\tau+\Delta\tau}$, $T^{i,j,h,\tau}$ – temperature on surface and inside h-th coil in time τ; $T^{i,j,h,(\tau+\Delta\tau)}$ – temperatures on surface and inside h-th coil in time $(\tau+\Delta\tau)$; a, b – coefficients of a line equation:

1. Reading the previous measurement time τ and actual measurement time τ_{finite} and calculation of period $\Delta\tau = \tau_{finite} - \tau$.
2. Reading of the coil configuration (number, ordering, dimensions, and matrix form and thermo-physical properties) and temperatures array in the coils respond to elected matrix forms (surface and inner temperatures of the coil h in the time τ - $T^{i,j,h,\tau}$, for i = 0, 1, 2, ..., m_h+1, j = 0, 1, 2, ..., n_h+1, h = 1, 2, ..., p) and atmosphere temperatures (T_A^{τ} in the time τ and $T_A^{(\tau+\Delta\tau)}$ in the time $(\tau+\Delta\tau)$).
3. Creation of the linear dependency between atmosphere temperature T_A^{τ} in the time τ (directly measured) and atmosphere temperature $T_A^{(\tau+\Delta\tau)}$ in the time $(\tau+\Delta\tau)$ defined for control and obtained from line equation for atmosphere temperature in dependence on time => $T_A^{\tau} = a + b.\tau$.
4. Calculation of the time step $\Delta\tau$ from stability condition (6) for needs of calculation the model of indirect measurement SIMIT from temperatures - $T^{i,j,h,\tau}$, i = 0, 1, 2, ..., m_h+1, j = 0, 1, 2, ..., n_h+1, h=1, 2,..., p.
5. If $(\tau+\Delta\tau) > \tau_{finite}$ then $\Delta\tau = \tau_{finite} - \tau$.
6. Calculation of the atmosphere temperature in the time $(\tau+\Delta\tau)$ => $T_A^{(\tau+\Delta\tau)} = a + b.(\tau+\Delta\tau)$.
7. Setup h=1 for calculation temperatures on surface and inside the coils.
8. Atmosphere temperature $T_A^{\tau+\Delta\tau}$ inputs to the model of indirect measurement SIMST. From this model surface temperatures are calculated on the coil with index h: $T^{i,0,h,(\tau+\Delta\tau)}$,

i = 0, 1, 2, ..., m_h+1, $T^{i,n+1,h,(\tau+\Delta\tau)}$, i = 0, 1, 2, ..., m_h+1, $T^{0,j,h,(\tau+\Delta\tau)}$, j = 0, 1, 2, ..., n_h+1, $T^{m+1,j,h,(\tau+\Delta\tau)}$, j = 0, 1, 2, ..., n_h+1 in the time $(\tau+\Delta\tau)$.

9. Temperatures inside the h-th coil in the time τ– $T^{i,j,h,\tau}$, i = 1, 2, ..., m_h, j = 1, 2, ..., n_h and coil surface temperatures in the time $(\tau+\Delta\tau)$ calculated in step 9 input to the model of indirect measurement SIMST. From this model we get temperatures inside the coil h in the time $(\tau+\Delta\tau)$ - $T^{i,j,h,(\tau+\Delta\tau)}$, i = 1, 2, ..., m_h, j = 1, 2, ..., n_h.
10. Storage of temperatures $T^{i,j,h,(\tau+\Delta\tau)}$, i = 0, 1, 2, ..., m_h+1, j = 0, 1, 2, ..., n_h+1 to the database of indirect measurement.
11. If $h = p$, then $\tau = (\tau+\Delta\tau)$ and following step 13, else $h = h + 1$ and step 9.
12. If $\tau = \tau_{finite}$, then step 14, else $T^{i,j,h,\tau} = T^{i,j,h,(\tau+\Delta\tau)}$, i = 0, 1, 2, ..., m_h+1, j = 0, 1, 2, ..., n_h+1, h = 1, 2, …, p, $T_A^{\tau} = T_A^{(\tau+\Delta\tau)}$ and jump to step 5.
13. End of calculation.

A presented algorithm is defined for one time period between two realized direct measurements of the atmosphere temperature.

3 Results and discussion

The verification of SITM consists of three parts. At the first step there was verified a model for indirect measurement of surface temperatures and the second step a model for indirect measurement of inner temperatures. The results of the model verification are presented at a form of average relative deviation (error) calculated by following equation:

$$\delta\_Tp_i = \frac{\sum_{j=1}^{k} \frac{abs\left(Tp_{i\,PM}^{\,j} - Tp_{i\,NM}^{\,j}\right)}{Tp_{i\,PM}^{\,j}} \cdot 100}{k}, \quad [\%] \tag{5}$$

where δ_Tp_i – average relative error of i-th surface temperature, $Tp_{\ i\,PM}$ – i-th direct measured surface temperature, $Tp_{\ i\,NM}$ – i-th indirect measured surface temperature (model), k – count of measurements.

After the verification both subsystems were verified SITM, with results that are presented at a graphical form shown on **Fig. 4 - 6**.

3.1 Results of a model for indirect measurement of surface temperatures

In **Tab. 1** there are presented results of the model for indirect measurement of each surface temperature. Average relative deviation of indirect measurement is from range 4 – 15%.

Table 1 Results of the model for indirect measurement in the form of average relative error for single surface temperatures

Tp	1	2	3	4	5	9	10	11	12	13
δ_Tp [%]	10.90	15.20	12.00	5.71	6.54	7.57	7.14	4.05	10.70	7.97

Table 2 Results of the model for indirect measurement in the form of average relative error for outer, inner side and the middle of the batch

Tp	outer side	inner side	middle
δ_Tp [%]	6.80	8.67	12.95

The highest deviation is at surface temperatures 1-3, which are placed on the bottom part of the batch (**Fig. 2**). Heat transfer from furnace base can influence on deviation in this place. In **Tab. 2** there are presented results of three models for inner side, outer side and the middle of the batch.

3.2 Results of a model for indirect measurement of inner temperatures

For verification of SIMIT there were directly measured three inner temperatures (T_6, T_7, T_8) these measuring places are shown on **Fig. 2**. In **Tab. 3** there are presented results of the SIMIT model for indirect measurement of the inner temperatures at directly measured surface temperatures. Verification of the model is presented in the form of average relative error calculated from equation (5), where instead of direct and indirect measured surface temperature T_p was placed direct and indirect measured inner temperature T_V [21, 22].

Table 3 The results of indirect measurement model in the form of average relative error for single inner temperatures

Tv	T_6	T_7	T_8
δ_Tv [%]	6.1	3.9	4.3

3.3 Verification of the system for indirect temperature measurement

SITM was verified on 12 measurements obtained from real operation. At these measurements there were measured 10 surface temperatures and 3 inner temperatures on each coil during a total annealing process. Single measurement positions are shown on **Fig. 2**. Various annealing modes were regarded at measurement, diameters and weights of the coils with a scope of wide verification of SITM, too. On next figures there are shown direct and indirect measured inner temperatures with utilization of SITM (T_6 – **Fig. 4**, T_7 – **Fig. 5**, T_8 – **Fig. 6**). From presented behaviours we can see qualitative accordance between direct and indirect measured temperature with a precision that satisfies requirement of the real operation on a quality of the information about inner temperatures of annealed coil.

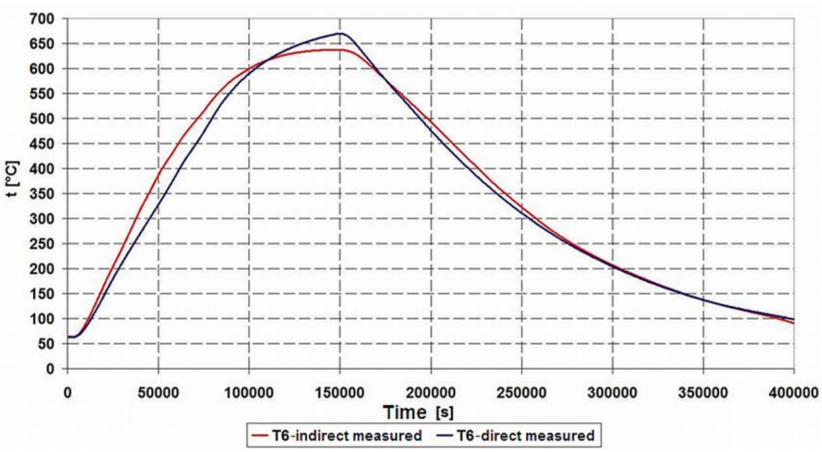

Fig.4 Comparison of direct and indirect measured temperature T_6

The results of SITM for indirect temperatures measurement in the steel coil are suitable within qualitative aspect that we can see on **Fig. 4-6**. From quantitative aspect there are results presented in the form relative deviation in **Tab. 1-3**. The highest deviation (12.95%) of the surface temperature is in the middle of the bath. At this place there are measured only two temperatures (**Fig. 2** - 2, 12) and on outer and inner side of the coil there were measured four surface temperatures (**Fig. 2** - 1, 4, 5, 11 respectively 3, 9, 10, 13). Number of measured temperatures has influenced on the model quality. The results of indirect measurement of inner temperatures are better at comparison with results of indirect measurement surface temperatures. This is important from aspect of the SITM function.

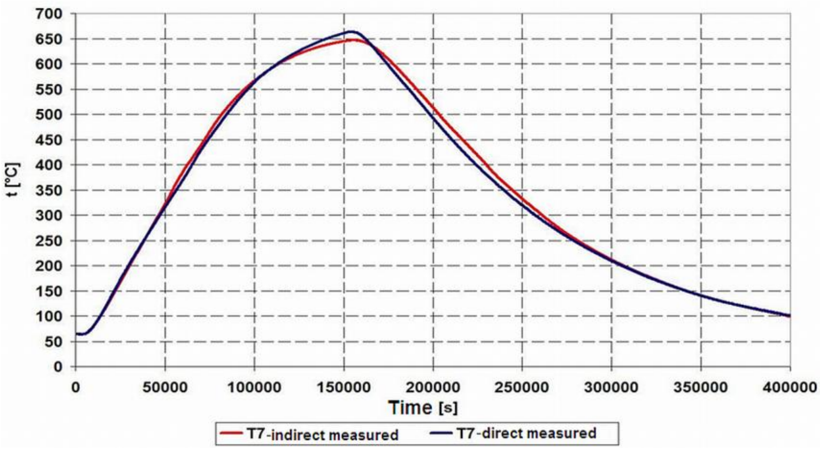

Fig.5 Comparison of direct and indirect measured temperature T_7

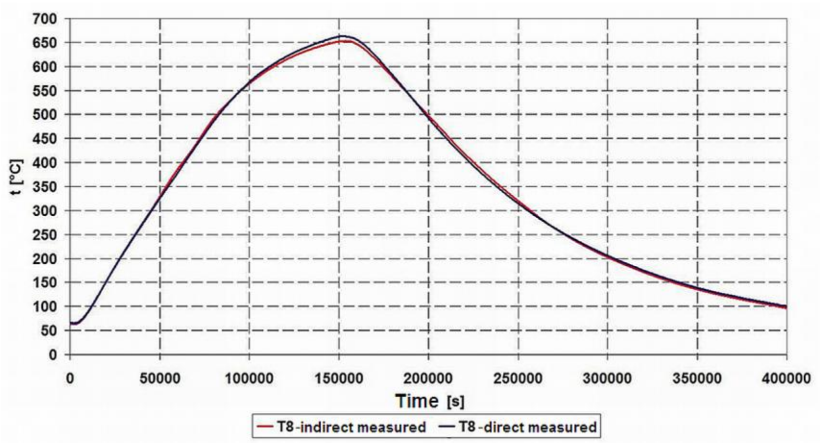

Fig.6 Comparison of direct and indirect measured temperature T_8

The SITM was solved and based on principle of neural networks in the past [13, 23]. This solution was applied only on the part of heating and holding in the annealing process. Behaviour of indirect measured surface temperature from the model based on principle neural network qualitative responds to the real temperature. Quantitative comparison of the results the proposed SITM and a model based on the principle of neural networks is not possible in due unavailability of quantitative evaluation (precision) of the model based on principle neural networks.

4 CONCLUSION

The acquisition of SITM we can see in two planes, in term of production quality and economics term. Quality of production is given by achieving of recrystallization temperature in a whole volume of annealed batch. If this temperature is not achieved then annealing quality is insufficient. Utilization of SITM enables to obtain information about temperatures in the batch and provides achieving recrystallization temperature.

By shortening of the annealing period so we have information about temperatures, the acquisition of SITM from economics term is following:

- increase the production of productivity,
- possible decrease count of equipment,
- saving mixture gas uses for annealing the steel coils,
- saving electric energy needed for several equipment of furnace.

Also there is possible effective control the annealing process of the steel coil with utilization of SITM.

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