Acta Montanistica Slovaca Ročník **13** (2008), číslo **1**, 94-99

The analysis of models for indirect measurement of surface temperatures in massive charge

***Marek Laciak*[1]*, Karol Kostúr* and *Martin Truchlý*[2]**

Analýza modelu pre nepriame meranie povrchovej teploty v masívnej vsádzke

In this article are described the models for indirect measurement of the surface temperatures in the steel coil. The indirect measurement of surface temperatures is part of intelligent system of indirect temperature measurement in the steel coil. The major task of this system is to measure massive charge temperatures in the annealing process continuously in time. In the design and creation of these models we used the fact that only one direct measured temperature of the atmosphere was at our disposal – the one under the protection cover. The created and verified models are in the form of difference equations and the surface temperatures depend on the atmospheric temperature only.

Key words: *indirect measurement, mathematical model, annealing process.*

The system of indirect temperature measurement

The task of the system of indirect temperature measurement in massive charge is the indirect measurement of internal temperatures during heat treatment. The system goes out the direct measured quantities and then it provides information about the temperature inside the charge. It's impossible to obtain this information without destructive measurement. Nowadays we can divide the system of indirect temperature measurement into two basic models (Fig. 1):

1. The model for indirect measurement of surface temperatures,
2. The model for indirect measurement of internal temperatures.

Both models are very important in the whole system of the indirect temperatures measurement. The internal temperatures inside the charge are calculated by the elementary balance method, following the surface temperatures. It was necessary to assemble models for indirect measurement of surface temperatures, because these temperatures are not measured directly. The model for indirect temperature measurement of the surface in massive charge calculates surface temperatures ($\mathbf{T}_{surface}$). These temperatures are calculated from directly measured temperature of the atmosphere (T_{atm}) and directly measured temperatures of the etalon ($\mathbf{T}_{etal}$). The internal temperatures ($\mathbf{T}_{internal}$) inside the charge are calculated from indirectly measured temperatures of the surface (Kostúr, 2005; Pástor, 2006).

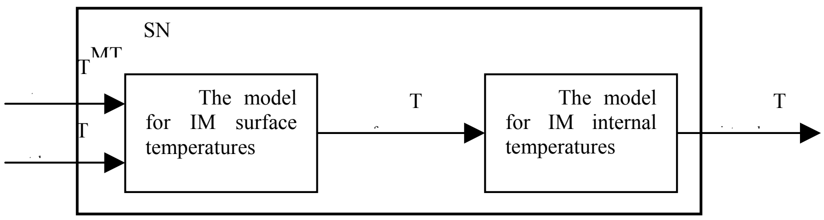

Fig. 1. Block scheme of system indirect measurement of temperature in massive charge.

The models for indirect measurement of surface temperatures

The models for indirect measurement of surface temperatures are assembled from the difference equations. During the annealing process only one temperature is still measured – protection atmosphere temperature. It was an effort to find out the models – the difference equations, by means of which we could measure the surface temperature indirectly through direct measurement of the protection atmosphere temperature.

[1] *Ing. Marek Laciak, prof. Ing. Karol Kostúr, CSc.,* Technical University of Košiciach, F BERG, Institute of Control and Inormatization of Production Processes, B. Nemcovej 3, Kosice 04354, marek.laciak@tuke.sk, karol.kostur@tuke.sk

[2] *Ing. Martin Truchlý*, Mi-Fi-BU, Skeleting s.r.o, N. Hutka 74, Košice 04018

(Recenzovaná a revidovaná verzia dodaná 28. 11. 2007)

The general form of the linear difference equation for the calculation of the surface temperature in dependence on the temperature of the atmosphere is as follows:

$$Tp_i[k] = \overline{a} \cdot \overline{T_{atm}}[k], \tag{1}$$

where Tp_i – i-th surface temperature of the coil, $\overline{a}$ - vector of the difference equation coefficients, $\overline{T_{atm}}$ -vector of the atmosphere temperature, k - time step.

For the verification of this methodology six models were designed, which differ by the number and by the form of independent inputs. The designed models have the following forms:

Model 1:
$$Tp_i[k] = a_0 + a_1 \cdot T_{atm}[k], \tag{2}$$

Model 2:
$$Tp_i[k] = a_0 + a_1 \cdot T_{atm}[k] + a_2 \cdot T_{atm}{}^2[k], \tag{3}$$

Model 3:
$$Tp_i[k] = a_0 + a_1 \cdot T_{atm}[k] + a_2 \cdot T_{atm}{}^{-1}[k], \tag{4}$$

Model 4:
$$Tp_i[k] = a_0 + a_1 \cdot T_{atm}[k] + a_2 \cdot T_{atm}{}^2[k] + a_3 \cdot T_{atm}{}^3[k], \tag{5}$$

Model 5:
$$Tp_i[k+1] = a_0 + a_1 \cdot T_{atm}[k+1] + a_2 \cdot T_{atm}[k] + a_3 \cdot T_{atm}{}^2[k], \tag{6}$$

Model 6:
$$\begin{aligned} Tp_i[k+1] &= a_0 + a_1 \cdot T_{atm}[k+1] + a_2 \cdot T_{atm}{}^2[k+1] + \\ &+ a_3 \cdot T_{atm}[k] + a_4 \cdot T_{atm}{}^2[k] \end{aligned}. \tag{7}$$

In the structure of six models (2) – (7) only one directly measured parameter features atmosphere temperature under the protection cover. The model was expanded to the next directly measured parameter.

The etalon was inserted under the protection cover. Nine thermocouples were inserted inside the etalon. (for direct measurement of nine temperatures). The etalon was made in the shape of the steel roll and its design met the Fourier criteria:

$$F_0 = \frac{a \cdot \tau}{h^2}, \tag{8}$$

where a – heat conductivity [$m^2.s^{-1}$],
h – typical distance,
τ - time [s].

The purpose was to find the material and dimensions of the etalon so that the value of the Fourier criteria of etalon (F_0^{etal}) approached the value for the same criteria in the real steel roll (F_0^{zvitok}).

The suitable material for the etalon is SIBRAL. The thermo-physical parameters of SIBRAL are very close to the value of the Fourier criteria for real steel roll. The placement of thermocouples (TE_1 – TE_9) in the etalon and their distances are presented in Figure 2. We decided for this placement of thermocouples because of the representative placement of thermocouples in real steel roll.

After application of etalon into the system of indirect temperatures measurement in the steel roll, model No 6 was extended with elements for directly measured temperature in the etalon. Two new models were created – Model No 7 (9) and Model No 8 (10). These models are extended by directly measured temperature in the etalon. In the model the temperature from the etalon shall apply, which responds to the surface temperature of the real steel roll.

Model 7:
$$\begin{aligned} Tp_i[k+1] &= a_0 + a_1 \cdot T_{atm}[k+1] + a_2 \cdot T_{atm}{}^2[k+1] + \\ &+ a_3 \cdot T_{atm}[k] + a_4 \cdot T_{atm}{}^2[k] + a_5 \cdot T_{etal}[k+1] \end{aligned}. \tag{9}$$

Model 8:
$$\begin{aligned} Tp_i[k+1] &= a_0 + a_1 \cdot T_{atm}[k+1] + a_2 \cdot T_{atm}{}^2[k+1] + \\ &+ a_3 \cdot T_{atm}[k] + a_4 \cdot T_{atm}{}^2[k] + a_5 \cdot T_{etal}[k+1] + a_6 \cdot T_{etal}{}^2[k+1] \end{aligned}. \tag{10}$$

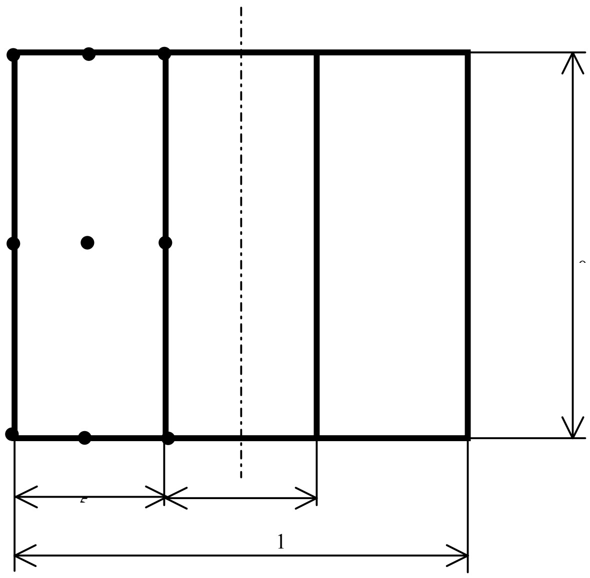

Fig. 2. Parameters of etalon and placement of thermocouples into etalon.

Verification of models in the system of indirect temperatures measurement

The verification of the created models for indirect temperatures measurement of surface consists of three parts. In the first part six models were verified in the complete annealing process. In the second part six models were verified in two various time phases of the annealing process (Fig. 3). The parameters of the model were calculated for the first phase (model 1) and for the second phase (model 2) of the annealing process. Both models have the same structure for each model of surface temperature (Model 1 – Model 6).

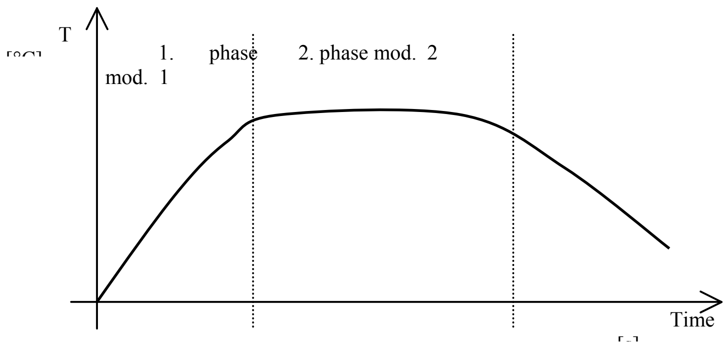

Fig. 3. Dividing the annealing process into two phases.

The first phase of these six models was realized on two working measurements, which were provided by U.S.Steel Košice s.r.o. In these measurements was measured only one surface temperature on every coil. In table 1 are presented results of various models for indirect measurement of the surface temperatures (T1 – 1.coil, T2 – 2.coil a T3 – 3.coil) in the form of average relative deviation (8). The parameters of the models – *a* are calculated from both measurements and the results are presented for both measurements too. (meas1 - measurement no.1 and meas2 - measurement no.2) (Kostúr, 2006).

$$\Delta\_Tp_i = \frac{\sum_{j=1}^{k} \frac{abs\left(Tp_{i\,PM}^{\,j} - Tp_{i\,NM}^{\,j}\right)}{Tp_{i\,PM}^{\,j}} \cdot 100}{k}, \qquad [\%] \qquad (11)$$

where Δ_Tp_i – average relative deviation of the i-th surface temperature, $Tp_{i\,PM}$ – i-th directly measured surface temperature, $Tp_{i\,NM}$ – i-th indirectly measured surface temperature (from the model), k – time step.

Tab. 1. The average relative deviations of the models M1 - M6 for the surface temperatures T1, T2, and T3.

The surface temperature		**T1**	**T2**	**T3**
Type of the model	**Measurement**	**Δ_Tp₁** [%]	**Δ_Tp₂** [%]	**Δ_Tp₃** [%]
M1	meas1	12.31	18.91	21.86
	meas2	3.36	6.13	6.45
M2	meas1	3.43	5.05	9.84
	meas2	1.76	2.57	3.49
M3	meas1	6.86	11.03	12.56
	meas2	3.46	5.96	7.01
M4	meas1	3.57	4.10	8.21
	meas2	1.75	2.83	3.18
M5	meas1	5.38	6.87	12.27
	meas2	1.94	2.58	4.19
M6	meas1	3.81	4.99	10.67
	meas2	1.70	2.47	3.78

From the results in table 1 it is obvious, that the best model for the surface temperatures T1 and T2 is model M6 and for the surface temperature T3 it is model M4. The worst results were achieved by model 1 and model 3 in the first measurement.

In the second part were verified six models in two time phases of the annealing process (Fig. 3), which were represented by two models (Dorčák, 2006). The division of annealing process into two time phases is the following. The first time phase is represented by one model - heating phase. The second time phase is the holding time phase. The results of models for three surface temperatures (T1, T2, T3) in three steel rolls are presented in table 2.

Tab. 2. The average relative deviations of models M1 - M6 for the surface temperature T1, T2, and T3 and for the division of the annealing process into two intervals.

The surface temperature		**T1**	**T2**	**T3**
Type of the model	**Measurement**	**Δ_Tp₁** [%]	**Δ_Tp₂** [%]	**Δ_Tp₃** [%]
M1	meas1	4.63	6.59	5.34
	meas2	1.43	2.98	2.93
M2	meas1	3.48	3.63	5.56
	meas2	1.48	2.41	2.46
M3	meas1	3.66	5.16	5.07
	meas2	1.56	3.09	2.44
M4	meas1	3.59	3.52	6.25
	meas2	1.71	2.42	2.43
M5	meas1	5.04	4.94	5.78
	meas2	1.59	2.13	2.39
M6	meas1	2.62	3.84	5.80
	meas2	1.29	2.39	1.94

By comparison of the results with one model and with two models during the annealing process, and comparing all the surface temperatures in terms of relative deviation, the better choice is using two models. In terms of average relative deviation of the models M1 - M6, the best choice is using the models M4, M5 and M6.

The third part of the verification was oriented toward the results of the models M7 a M8 with directly measured temperatures in the etalon. These models were verified in both previous parts - with one model for the complete annealing process and with two models for the process divided into two phases. In previous two measurements the etalon was not used, therefore it was necessary to make new measurements with the placement of the etalon under the protection cover. Three measurements were made in May 2007 with direct temperature measurement in the etalon (meas3, meas4, meas5). In previous two measurements only one surface temperature in each of three steel rolls was measured. In new measurements there were ten thermocouples placed in each steel roll for the surface temperature measurement and three thermocouples for the inside temperature measurement. The placement of the etalon and steel rolls under the protection cover is shown in Fig. 4.

The results for surface temperatures T1, T2 a T3 - placed in the bottom roll (roll 1) are presented in tab. 3 as the average relative deviation.

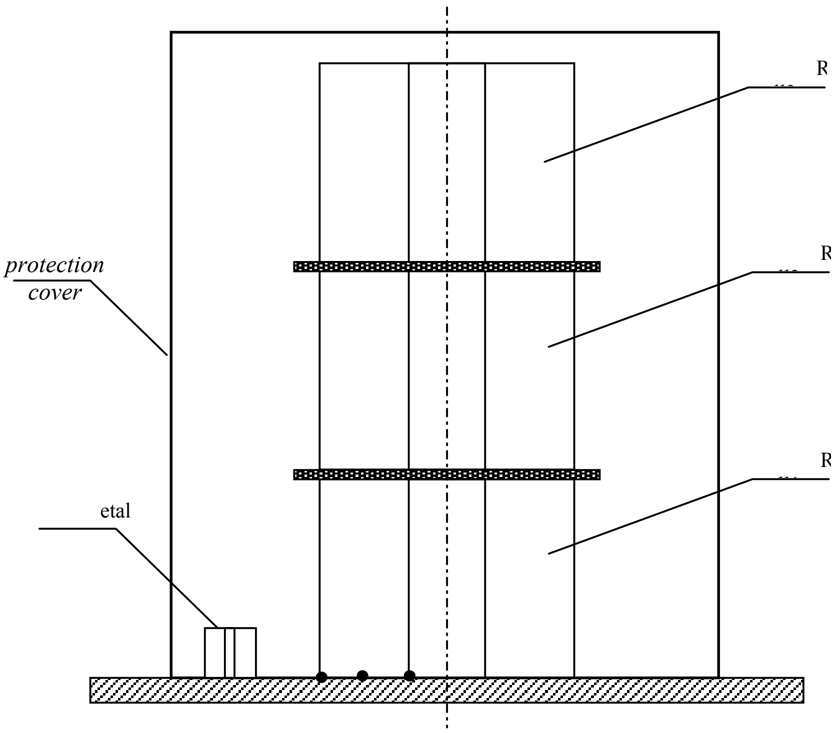

Fig. 4. The placement of etalon and steel rolls under the protection cover of annealing furnace.

Tab. 3. The average relative deviation of models No 7 and No 8 for surface temperatures T1, T2, and T3.

The surface temperature			T1	T2	T3
Type of the model		Measurement	Δ_Tp1 [%]	Δ_Tp2 [%]	Δ_Tp3 [%]
1 model	M7	meas3	0.79	15.25	8.07
		meas4	0.53	20.95	7.89
		meas5	7.08	12.17	4.58
	M8	meas3	0.48	7.33	8.72
		meas4	0.47	8.42	8.20
		meas5	7.32	4.43	4.51
2 models	M7	meas3	0.42	3.17	3.44
		meas4	0.89	4.09	4.87
		meas5	7.78	5.50	4.45
	M8	meas3	0.33	2.23	1.02
		meas4	0.43	2.41	1.15
		meas5	7.18	3.80	4.55

By comparing model 7 and 8, which were verified on the measurements 3,4 and 5, in view of the achieved results, model 8 was better than model 7. The best results were achieved by indirect measurement of the surface temperature T1 (besides measurement 5), where the achieved average deviation was under 1 %.

Conclusion

For indirect temperature measurement in the massive charge eight models were made and verified in three parts. In the first part one model for the complete annealing process was made, and it was verified in the measurements 1 and 2. In the second part the annealing process was divided into two phases (heating phase and holding time phase). Two models represented these phases. The third part was verified on two models (M7 and M8). In these models, apart from direct measured temperature of atmosphere, directly measured temperature of the etalon was used. Moreover, these models were verified for the division of the annealing process into two phases and for the whole of the annealing process too. From the viewpoint of the average of the models, represented by the average relative deviation, the third variant was the best (M7 and M8). For a better verification of the models more measurements are needed.

Acknowledgements: *This work was partially supported by grants VEGA 1/3346/06, 1/2179/05, 1/2160/05 and AV 4/0016/05 from the Slovak Grant Agency for Science.*

References

Kostúr, K., Laciak, M., Truchlý, M.: Systems of indirect measurement. monograph, *Reprocentrum, Košice, march 2005, 173 pp. ISBN 80-8073-273-6.*

Kostúr, K.: Intelligent system of indirect measurement of temperature. Annual report about solution of project, *december 2006*.

Dorčák, Ľ., TERPÁK, J.: Monitoring and Prediction of the Liquid Steel Temperature in the Ladle and Tundish. *Metalurgija, Vol.45, No. 2, 2006, ISSN 0543-5846, pp.93-96*

Pástor, M., Truchlý, M., Kostúr, K.: The proposal of heat fow sensor In: ICCC '2006 : Proceedings of 7th international Carpathian control conference, *Rožnov pod Radhoštěm, Czech Republic, May 29-31, s. 409-412, Ostrava, 2006. - ISBN 80-248-1066-2*.