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# MODELING AND DATA RECONCILIATION OF THE HEAT RETAINING PANEL SYSTEM OF HOT STRIP MILL

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**Abstract**. The aim of this work is the modeling of the process of cooling of a metal plate in the presence of thermal reflecting panels on the intermediate table of a hot strip mill. A mathematical model of the process of cooling has been developed in order to study the temperature behavior in the metal under different initial and boundary conditions. The problem of reconstruction of temperature field in a metal plate is investigated, as well as methods for its decision. Also the problems of data reconciliation and fault measurement diagnosis are discussed in this paper. The soft computing method is implemented in a combination with the mathematical model of the cooling process of the metal. The obtained results show that this method is a suitable and powerful tool, capable to eliminate the initial uncertainties in temperature measurement and to estimate the temperature profile inside the strip.

**Key words**. Modeling, heat retaining panel system, data reconciliation, soft computing method

## 1. INTRODUCTION

The search for intelligent solutions necessarily addresses (a) the identification of models (whether implicit in expert rules or explicit in differential equations), (b) the definition and computation of acceptable solutions, and (c) the robust synthesis of information from multiple sources. Modeling has long been the cornerstone of the engineering approach to problem solving. Models are essential components of problem-solving methodologies used to tackle process engineering.

Monitoring and diagnosis of process operations have been a very fertile ground for the theoretical development and industrial deployment of intelligent systems. The reliable data in industrial systems are of great importance for their computer simulation, automatic control and optimization.

The research interest has been long time concentrated on the problem of correction and diagnosis of gross mass flow rates errors, where good solving algorithms have been presented [7,8]. However, they usually deal with the case of a single set of fault measurements for the investigated system. Even though there are a lot of works in the field of data reconciliation and diagnosis [2], still there is a lack of satisfactory algorithms for temperature errors correction and diagnosis in real industrial systems. The procedures for diagnosis and data reconciliation work only under the condition of over determined balance parameters in the plant. Unfortunately this is not the real case in the industrial plants where quite often there are just a few available sensors for flow rates and/or temperatures and moreover not all of them work properly. In such a quite difficult but real situation still smooth and save operation of the plant is a desired action and any methods and procedures being able to help are highly appreciated. Quite interesting approach to solving partly such a problem is to introduce the so called software (inferential or "model based") sensors. These are not real sensors but just a models evaluating the missing real measurement by using another set of input data which are in a "cause-effect" relationship with the missing measurement.

In a recent research [1,10] on the measurement correction and diagnosis the so called "faulty degree" of each sensor has been introduced thus enabling the correction procedure in the case of many (practically almost all) wrong sensors. This method is quite suitable to be used in the case of the software sensors, where a faulty degree also can be defined. In this paper a soft computing method for data reconciliation [10] has been proposed and applied to the system of thermal insulation panels on the intermediate table in a hot strip mill.

As it is known from the technological scheme of the manufacturing process of hot rolled strip, before entering the finishing group for a final deformation, the metal bars go along the intermediate table of the hot strip mill. In this area they lose a serious part of their heat because of the heat exchange with ambient air and the different speeds of movement of the intermediate table and the finishing group. As a result a temperature difference between the front end and the back end of the sheets can be observed. In many cases it is significant. This makes the quality of the final product worse, because the metal strip should enter the first stand of the finishing group with an even temperature distribution along its length and its thickness and with as much higher temperature as possible. An effective way effective way to keep a maximum amount of heat in the metal and to avoid the large temperature difference along the strip length is to cover the intermediate table with a system of heat retaining panels [4, 5, 6].

This paper deals with the process of cooling of a thick metal sheet during its movement on the intermediate table and studies the influence of the heat retaining screens on the heat conservation in the strip. A mathematical model has been developed, predicting the temperature distribution inside the metal and the screens, at changeable initial and boundary conditions. The major difficulty in studying the temperature profiles is the fact that the temperature can only be measured on the surface of the bar and the screen [9]. Because of the lack of measurement data a reliable correction procedure is necessary. Here the soft computing method for data reconciliation and fault measurement diagnosis is used. The obtained results show that these procedures are applicable and suitable for the discussed system and using them, the influence of many factors on the thermal state of the metal have been studied.

## 2. MATEMATICAL MODELING OF THE HEAT TRANSFER

The technological scheme of the process of cooling of a metal plate in the presence of thermal reflecting panels on the intermediate table of a hot strip mill is presented at Fig. 1.

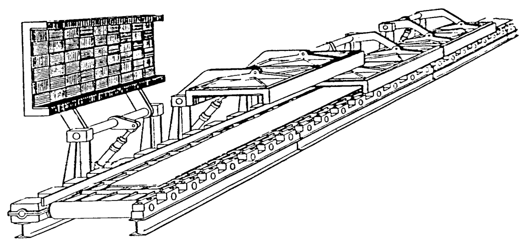

Fig. 1. Heat retaining panels system on the intermediate table of the hot strip mill

A mathematical model is created to predict the temperature distribution in the system metal – surrounding panels, under changing boundary conditions. The effect of different factors, influencing the change in the metal temperature profile, is studied. Many simulation experiments have been carried out, the results of which may be used to find the optimal dimensions of the insulating panels in order to achieve a constant temperature at each point of the sheet before its rolling and to preserve maximum quantity of heat in it. The guaranteeing of these factors is very important from a technological point of view, so that after leaving the finishing group to obtain a strip with a uniform, steady temperature distribution, which will lead to the obtaining of a final product with the desired quality.

The metal cooling process on the intermediate table has two aspects. On the one hand, this is the heat exchange between the surface of the heated metal and the environment and the surfaces of the insulating panels. This is the external problem. The determination of the temperature distribution inside the sheet, as well as inside the surrounding panels, is the so cold internal problem. As in the external heat exchange the major part belongs to radiation because of the high temperatures, for the calculation of the heat fluxes the zonal method is used. Both the metal and the reflecting panels have been separated on several zones. The illustration of this calculation method is presented at Fig. 2. The heat transfer of each zone of the metal sheet and of the insulating panels has been considered.

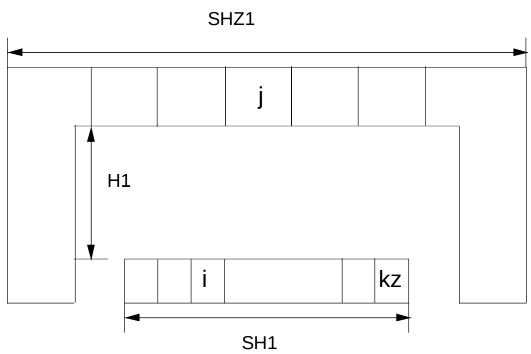


Fig. 2. Zonal separation of the metal and the panels

For determination of the resulting heat flux of each zone of the metal sheet the following equation is used:

$$Q_I^{res}.A_i = A_i.Q_I^{ef} - A_i.Q_I^{fall} \qquad (1)$$

where:
$Q^{res}$ – a resultant heat flux from zone $i$ to all the other zones, [W];
$Q^{ef}$ - effective heat flux of zone $i$, [W];
$Q^{fall}$ - heat flux falling on zone $i$ from all the other zones, [W];
$A_i$ - surface area of zone $i$, [m$^2$];
$i$ - $1 \div kz$ - number of the zones in the metal sheet.

The similar equations to (1) could be used for determination of the resulting heat flux of each zone $j$ of the retaining panels. The calculations of $Q^{ef}$ and $Q^{fall}$ have been performed in the following way:

$$Q_I^{ef} = \varepsilon.\sigma.\theta_i^4 + (1-\varepsilon).Q_i^{fall} \qquad (2)$$

where:
$\varepsilon$ - degree of blackness of zone $i$;
$\theta_i$ - temperature of zone $i$;
$\sigma$ - emission coefficient of the absolute black body.

In order to determine the heat flux falling on the surface of zone $i$, we need to know the angle coefficients between the zones participating in the heat exchange. This heat flux is calculated according to the next equation:

$$Q_i^{fall} = \sum_{j=1}^{mz} \varphi_{ij}.Q_i^{ef} \qquad (3)$$

where $\varphi_{ij}$ is the corresponding angle coefficient between zones $i$ from the metal and $j$ from the panels. The resultant heat fluxes $Q_i^{res}$ and $Q_j^{res}$, determined in this way, are set as boundary conditions to the internal heat exchange problem.

To find the temperature distribution inside the metal sheet, as well as inside the reflecting surfaces, the two-dimensional non-linear transient heat transfer equation is used:

$$c(\theta)\rho(\theta)\frac{\partial\theta(\tau,x,y)}{\partial\tau} = \lambda(\theta)\frac{\partial^2\theta(\tau,x,y)}{\partial x^2} + \lambda(\theta)\frac{\partial^2\theta(\tau,x,y)}{\partial y^2} \qquad (4)$$

where $\lambda = \lambda_m, \lambda_p$ is the heat conduction coefficient of metal and surrounding panels correspondingly, [W/m.K];
$c = c_m, c_p$ - specific heat capacity of metal and the panels, [J/kg.K];
$\rho_m$ , $\rho_p$ - density of metal and the panels, [kg/m$^3$];
$\theta$ - temperature of a given node of the investigated cross-section of the plate and the panels, [$^0$ C];
$x, y$ - space dimensions, [m];
$\tau$ - time , [s].

In this case the internal conditions are unsteady and have the following form:

$$\theta(0, x, y) = \theta_{0i}(0, x, y) \qquad (5)$$

$i = 1,k$ - number of the node in the studied cross-section of the body.

The decision of equation (4) is found through the finite difference method, using the explicit numerical technique. It determines the temperature distribution in a given cross-section of the body for each zone of metal or the insulating surfaces. Fig. 3 presents the scheme of the space discretization of one cross-section of the metal sheet or the screens. The thermophysical properties are non-linear functions of temperature. They are determined depending on the mean temperature of the body - metal or panels.

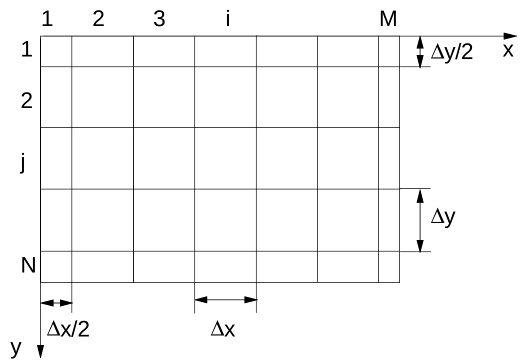


Fig. 3. Space discretization in the cross-section of metal (panel)

The boundary conditions (Fig. 4) are determined by the decision of the external heat transfer problem (it has already been discussed above), written for each zone of the metal plate and the reflecting surfaces, and have the following form:

$$\lambda(\theta)\frac{\partial\theta_m}{\partial x}\Big|_{x=0} = Q_{3,i}^{res}$$
$$\lambda(\theta)\frac{\partial\theta_m}{\partial x}\Big|_{x=M} = Q_{4,i}^{res}$$
$$\lambda(\theta)\frac{\partial\theta_m}{\partial y}\Big|_{Y=0} = Q_{1,i}^{res} \qquad (6)$$
$$\lambda(\theta)\frac{\partial\theta_m}{\partial y}\Big|_{Y=N} = Q_{2,i}^{res}$$

$i = 1 \div kz$ – number of the zones of the metal.

For the panels:

$$
\begin{aligned}
&\lambda(\theta)\frac{\partial \theta_p}{\partial x}\Big|_{x=0} = Q^{\text{res}}_{10,j} \\
&\lambda(\theta)\frac{\partial \theta_p}{\partial x}\Big|_{x=M_1} = Q^{\text{res}}_{9,j} \\
&\lambda(\theta)\frac{\partial \theta_p}{\partial y}\Big|_{Y=0} = Q^{\text{res}}_{7,j} \\
&\lambda(\theta)\frac{\partial \theta_p}{\partial y}\Big|_{Y=N_1} = Q^{\text{res}}_{6,j}
\end{aligned}
\tag{7}
$$

$j = 1 \div mz$ - number of the zones of the panels.

$$Q^{\text{res}}_{2,i} = -Q^{\text{res}}_{5,i} \tag{8}$$

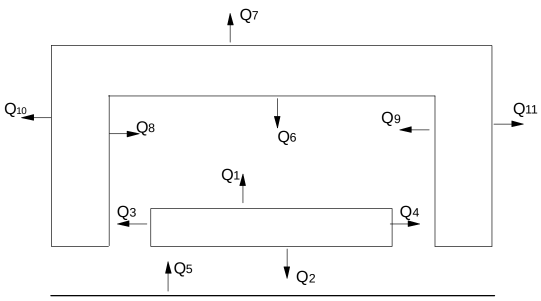


Fig. 4. Heat fluxes in the system metal - retention panels - intermediate table

## 3. SOFT COMPUTING METHOD FOR DATA RECONCILIATION

The major difficulty in studying the temperature profiles is the fact that the temperature can only be measured on the surface of the bar and the screen. No information is available about the real temperature field along the metal thickness. The surface temperature measurements are not very reliable, because of the so called "black spots", caused in the reheating furnaces (these are zones with a lower temperature than the rest of the surface). Another reason is the oxidation layer formed by the contact with ambient air. That is why, in order to use this information, a reliable correction procedure is necessary. The soft computing method for data reconciliation and fault measurement diagnosis is used here in a combination with the mathematical model of the heat transfer in the system intermediate table - heat retaining panels - metal sheet.

The problem of temperature measurement correction on the base of the heat balance system of equations has been discussed in [1]. In order to solve the diagnostic problem, a combinatorial procedure with appropriate criteria have to be constructed. In [1] the following 2 performance criteria have been proposed: $Q_1$ evaluates the errors in correction procedure and $Q_2$ takes into account the structural as well as technological constraints for the real system under investigation. Then the proposed in [1] procedure for faulty temperature measurements diagnosis has to be performed.

Since the number of real sensors is not sufficient to run the classical correction procedure, the missing data are replaced by their evaluation by respective inferential sensors. Then the soft computing method [10] for diagnosis and correction is applied in the case of preliminary available information about the faulty degree of some (or all) software sensors. In the followings the outlines of the soft computing method are given. This is a simple heuristic method of finding equivalent solutions for the fault diagnosis procedure. It uses random search technique where a preliminary given number of P random Hypothesis Patterns (vectors) is generated. The main steps of this optimization method are as follows:

1. Generate randomly the *current* Hypothesis Pattern (vector) $\mathbf{H}_p = \{ h_1, h_2, \ldots h_r, \ldots h_{n+m}\}$, $(1 \le p \le P)$;
2. Perform the modified measurement correction procedure [10] for the generated vector $\mathbf{H}_p$. Calculate the respective relative errors $x_r$, $r \in \mathbf{R}$.
3. *Fuzzify* the relative errors $x_r$ obtained, according to the maximum expected value $x_{rmax}$ as a deviation from the normal (true) case [3]. As a result the vector $\mathbf{S}_q = \{s_1, s_2, \ldots, s_r, \ldots, s_{n+m}\}$ is obtained.
4. By using the *C-means* algorithm for *cluster analysis* [3] divide the elements in $\mathbf{H}_p$ as well as the elements in $\mathbf{S}_p$ into 2 *crisp* clusters representing *true* and *faulty* measurements. Then the measurements defined as clearly *faulty* in both vectors $\mathbf{H}_p$ and $\mathbf{S}_p$ form the respective clusters $\mathbf{C}_H$ and $\mathbf{C}_S$. Here $\mathbf{C}_H$ represents the hypothesis for faulty instruments while $\mathbf{C}_S$ is the calculated faulty status of the instruments.
5. Check the *feasibility* of the current hypothesis $\mathbf{H}_q$. If $\mathbf{C}_S \subset \mathbf{C}_H$ then a conclusion that $\mathbf{C}_S$ is a *candidate solution* is made. Otherwise *Go to Step* **7**.
6**.** Calculate performance index Q for the current candidate solution $\mathbf{C}_S$ as follows:

$$Q = K\sum_{j\in J} h_j\sigma_j + \sum_{j\in J}(1-h_j)\left|x_j\right| \tag{9}$$

If $Q \le Q_{min} + \Delta$, ($Q_{min}$ is the current minimal obtained value) then this candidate solution is called *equivalent candidate solution* and it is saved, otherwise it is discarded.
7. If $p \le P$ *Go to Step* **1**; otherwise *Stop*.

The most important advantage of this Soft Computing Method is that it replaces the generally used *exhaustive search* or *branch and bound* techniques in the crisp method by a *non-linear programming* procedure, more suitable for solving large scale problems. It is also shown that the proposed method can successfully deal with the more general case of having two types of measurements: *real* ones (by *real sensors*) and *inferred data* measurements by use of the so called *software sensors*.

## 4. SIMULATION RESULTS

With the help of the model and the soft computing method for data reconciliation, discussed above, was traced the behavior of the temperature field in metal under different cooling conditions. The aim of these investigations is to find the optimal geometrical parameters of the insulating chamber, that guarantee preservation of maximum quantity of heat in metal before rolling in the finishing group, as well as to predict dynamically its temperature during its movement on the table.

An example of the simulated experiments is shown on Fig. 5 a, b. The temperature change along the intermediate table length is calculated in the cases when the insulating screens are on the table and when they are absent (Fig. 5.a.). In the first case the metal sheet reaches the end of the table with a higher mean temperature, which proves the effectiveness of the panels for the preservation of heat inside metal. Fig. 5.b. shows the temperature change in the metal and in the heat retaining panels during their movement on the table. The conditions of the experiment are as follows:

- initial temperature of the metal – 900 °C;
- initial temperature of the panels – 40 °C;
- time of the discretization – 1 second;
- thickness of the metal – 0,030 m;
- width of the metal – 2,200 m;
- thickness of the panel – 0,030 m;
- width of the panel – 2,200 m;
- distance between the panel and the metal – 0,200 m;
- emissivity of the metal and the table - 0,8;
- emissivity of the screens - 0,5.

The following cases were studied:

1. Influence of the speed of movement of the plate on its temperature profile. The results show that higher speeds lead to higher heat preservation in the body, but the temperature profile is not steady. Here a trade-off between these two factors must be found in order to achieve good results (Fig. 6).

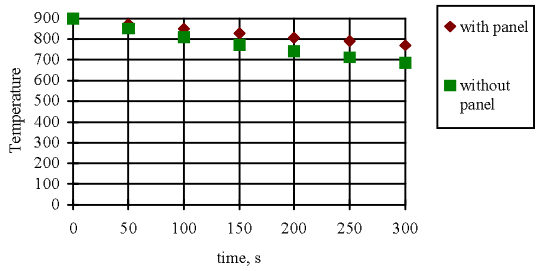


Fig. 5.a. Change of the temperature in the metal

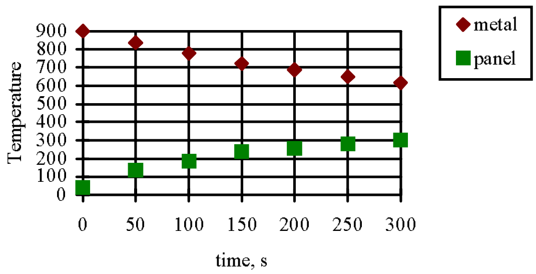


Fig. 5.b. Change of the temperature in the metal and in the panels

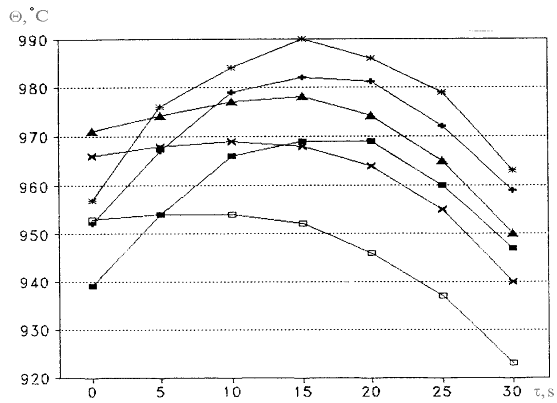


Fig. 6. Influence of the speed of movement of the bar on the temperature profile

2. Ability of the heat retaining panels to influence the uniformity of the temperature distribution along the length of the sheet. Fig. 7. a, b illustrate the effect of the heat retaining panels system on the uniform distribution of the temperature inside metal They show the temperature profile at the beginning of the heat retention panes zone and at its end in case when the screens are on the table and when they are absent. It is obvious that in the first case the temperature profile is much more uniform and the temperature inside metal is higher.

The simulation experiments lead to the conclusion that the geometrical dimensions of the insulation system on the intermediate table are of great importance for the temperature distribution in the metal strip. The height of the panels over the table has significant influence, as well as their width. The results show that in order to be effective for a large range of sheet widths, the panels should not be placed higher than 200 mm over the table.

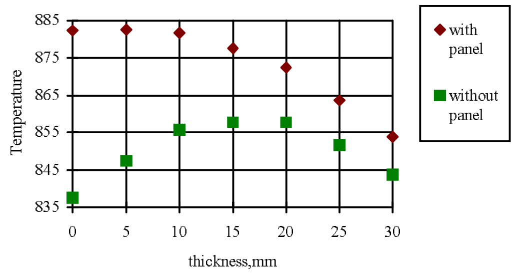


Fig. 7.a. Temperature profile inside metal sheet before the zone with the insulating screens

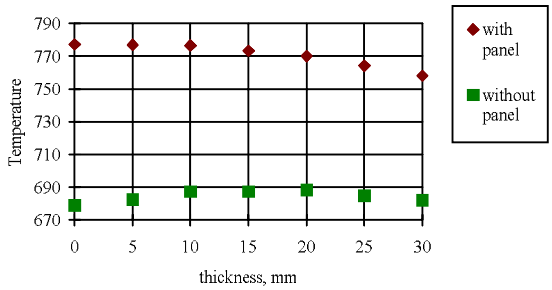


Fig. 7.b. Temperature profile inside metal sheet at the end of the zone with the insulating screens

The effect of the metal sheet thickness was also investigated. It was noticed that in the thinner bars (thickness 4mm to 20 mm) the % of the preserved heat quantity is greater than in the thicker ones, which means that the positive effect of the heat retaining panels is greater on the thinner bars than on the thicker ones.

## 5. CONCLUSIONS

The system of thermal insulation panels on the intermediate table in a hot strip mill makes possible to preserve a higher amount of heat inside the metal sheet and to achieve a more even temperature distribution before its rolling in the finishing group. This significantly facilitates the subsequent deformation of the bar and ensures optimal conditions for the formation of the final microstructure inside the metal strip during its cooling on the runout table. Having in mind that the physical measurements of the internal metal temperature on the intermediate table are not possible, it is very important to find an appropriate way to study the temperature field inside it. The surface temperature measurements are not enough as an information to estimate the thermal state of the strip, besides it is not reliable due to the "black spots" caused by the heating in the reheating furnace. That is why the soft computing method is implemented in a combination with the mathematical model of the cooling process of the metal. The obtained results show that this method is a suitable and powerful tool, capable to eliminate the initial uncertainties in temperature measurement and to estimate the temperature profile inside the strip.

## 6. REFERENCES

[1] Christova N., 1999, *Ph.D. Thesis on Diagnosis and Correction of Complex Measurement Errors in Technological Systems*, Sofia.
[2] Crowe, C.M., 1994, Data Reconciliation - Progress and Challenges, Proceedings of *PSE'94*, Seoul, p. 111.
[3] Hirota K., W. Pedrych, 1983, Analysis and Synthesis of Fuzzy Systems by the Use of Probabilistic Sets, *Fuzzy Sets and Systems*, v. 10, No. 1, p. 1.
[4] Ginzburg V., F. Bakhtar, R. Dittmar, Theory and design of retaining type heat retention panels, *Iron and Steel Eng*., pp. 17-25, Dec. 1989.
[5] Laws W. R., G. R. Reed, E. C. Hewitt, T. M. James, New roller table thermal insulation systems increase product range and save energy in hot strip mill, *Proc. of the 4th Int. Steel Rolling Conf*., vol. 1, Dauville, France, p. A.6-1 - A.6-7, 1987.
[6] Laws W. R., G. R. Reed, Y. J. Walker, R. Nickolls, Heat conservation during hot rolling of beams and sections: The Encoscreen", *Iron and Steel Eng*., pp. 37-41, January 1990.
[7] Mah, R.S.H. and A.C. Tamhane, 1982, Detection of Gross Errors in Process Data, AIChE J., 28, pp. 828-837.
[8] Romagnoli J. A., G. Stephanopoulos, 1981, On the Rectification of Measurement Errors for Complex Chemical Plants, *Chem. Eng. Sci*., 35, p. 1067.
[9] Upton E., D. Heflin, R. Mintus, R. Zenner, Heat retaining panel performance at a 56-in. hot strip mill, *Iron and Steel Eng*., pp. 24-29, June 1989.
[10] Vachkov G., N. Christova, Soft Computing Method for Solving the Problem of Diagnosis and Correction of Measurement Errors, *Computers Chem. Engng*., v. 20, Suppl., 1996, S659-S664.