Water flows' management system at the secondary cooling in the continuous steel casting process

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Abstract: - In this work it was proposed the structure of a management system for the water flows in the secondary cooling area within the continuous steel casting process.

The management system assumes the utilization of some temperature and speed transducers, of which output measures represent the input variables for the Fuzzy regulator. For adapting the output measures from transducers with the inputs of the Fuzzy regulator, it was conceived an adaption system that achieves the variation range 1-100%.

For implementing the expert system, it was achieved a base of specific knowledge, introduced by the human expert and materialized as some sets of rules that constitute the reasoned judgement based on which the system is acting by analyzing the variables' real values.

Key-Words: - translation circuit, continuous casting, water flow, secondary cooling, Fuzzy controller

1 Introduction

In the hierarchical lay-out of the production process' automatic management system at the continuous steel casting installations, on the lowest level are the closed control loops that work in direct connection with the continuous casting line's units and installations, followed by the process' management system, that monitors and controls the entire production process. On top of the pyramid is a computer for management and planning, that achieves, mainly, commercial operations.(fig.1)

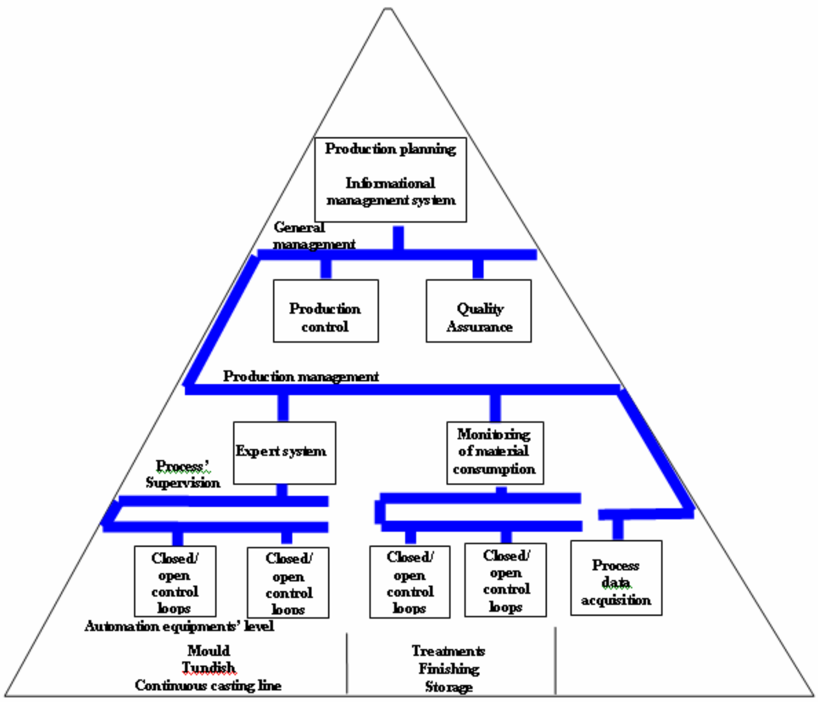


Fig. 1 Hierarchical lay-out of the production process' automatic management system at the continuous casting installations

By automation of a continuous steel casting installation is aimed the production of a maximum steel quantity of the desired quality and dimension, with a minimum energy consumption, equipments' protection and personnel's rational utilization.

Introducing of PLCs for solving the management sequences for normal operation represents an essential simplification in the technological process' management.

By complex automation of the continuous steel casting installations are ensured the following advantages:

- obtaining of a better product quality by cooling's control, correlating continuously the withdrawal speed by crust's growth;
- quality increase and reducing the quantity of rejects by modernization and continuous assessment of all parameters during the casting process, in order to ensure an efficient cutting system, to eliminate defect products with minimum costs;
- solving efficiently some conflictual situations during the casting process, based on the suggestions provided by the computer by chosing the less unfavorable situations;
- ensuring the process parameters imposed by their calculation by a well-established algorithm and their modification on time, depending on the current requirements;
- automatic calculation of the strand's cutting lenghts depending on the required product dimensions;
- ensuring an efficient and uniform control of the cast product by continuous dialog between the management system and the steel making shop.

2 Structure of the water flows' management system at the secondary cooling using the Fuzzy logic

2.1 General presentation of the management system

The requirements imposed to the technological processes refer both to the qualitative indices of the achieved products and the economical aspects (productivity, cost price, operation costs, removal of rejects, environment protection etc.).

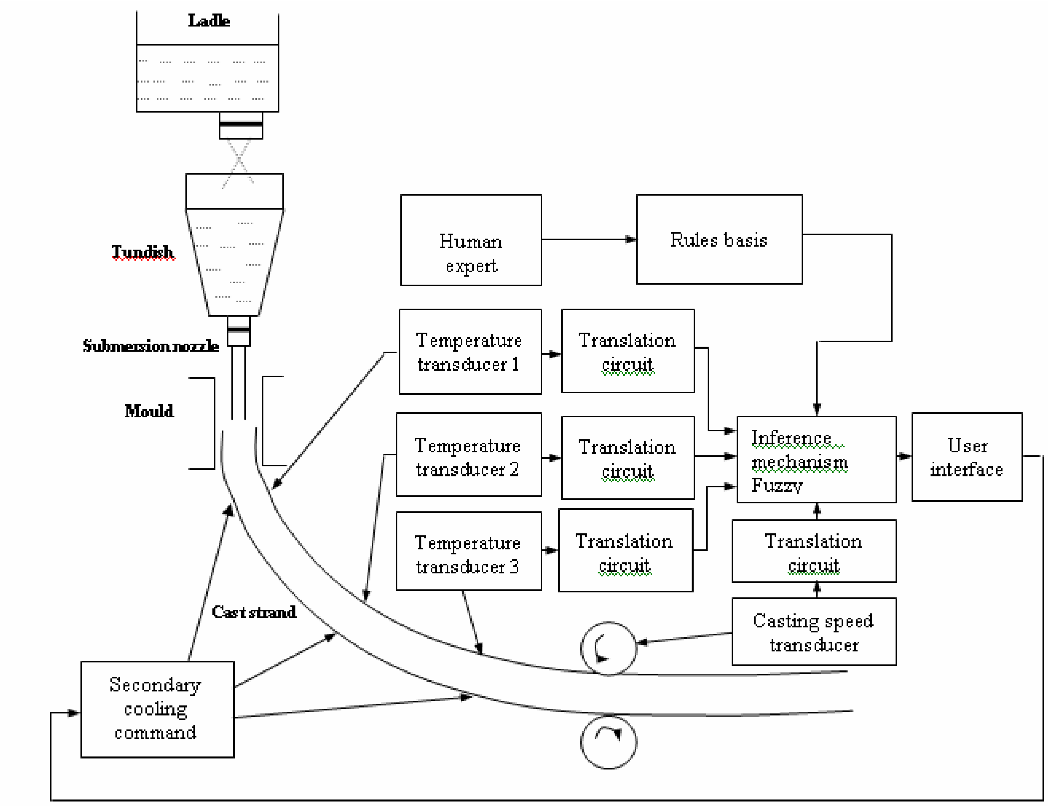


Fig. 2 Block diagram of the system based on Fuzzy logic

The steel's continuous casting is a technological process where the parameters should be very strictly controlled, is hard to be accurately mathematically modelled due to the complexity of the composing phenomena and where the automatic control's quality is determinant for the product's final performances. [1]

The secondary cooling's purpose is to continue the strand's cooling after it came out from the mould and to solidify completely the strand's cross-section. The secondary cooling area follows immediately after the mould and generally it extends over 30 % ÷ 50 % of the liquid core's length. It is divided in subzones, which are individually controlled. The cooling environment in this area is the water, or a mixture of air and water, sprayed by nozzles on the strand's surface, and the water flow is controlled so that the strand's surface temperature decreases uniformly in the casting direction. The temperature should be constant on the strand's circumference, in order to avoid the local overcooling. The secondary cooling should not be too intense, for not causing the sudden decrease of the strand's temperature, which might determine local thermal stress in the crust and, as consequence, internal and superficial strand's cracking.[2]

Modification of the casting speed should lead to the modification of the material's cooling regime. Its management through analogue adjustment loops does not take into account a series of anticipative effects produced by the steel level adjustment in the mould. Also, is not taken into account the material's temperature decrease slope.

Improvement of the presented situation can be achieved using an expert system, which imposes the installation's operation with optimal parameters taking into account the qualitative modification of the steel's characteristics in the continuous casting process. The structure of the proposed system (fig. 2) assumes the existence of some temperature transducers disposed in different spots in the secondary cooling. [5]

For adjusting the water flows at the secondary cooling, as important for the process are considered the following measures:

- the input variables are: withdrawal speed, material temperature in zone 1, material temperature in zone 2 and material temperature in zone 3,
- the output variables are : cooling water flow in zone 1, cooling water flow in zone 2 and cooling water flow in zone 3.

Analysing from technological viewpoint the measures taken in consideration, an expert can establish, by the elaborated sets of rules, adequate values for the execution mechanisms. Having in view the great number of variables taken in consideration for each adjusted parameter, could be obtained a precision clearly superior to the current situation.

2.2 Adaption Circuit of the Control Voltage For Fuzzy Algorithms' Application

The principle diagram of the adaption circuit (fig. 3) contains three variation steps corresponding to the three variation fields of the steel temperature from the secondary cooling area.

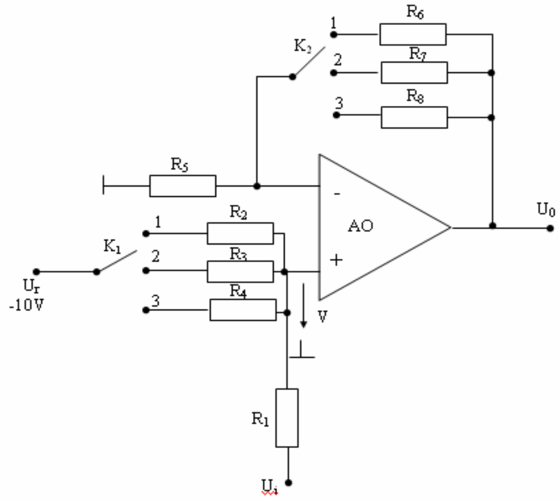


Fig.3 Principle diagram of translation circuit

The three variation steps appear from the need to correct the non-linearity of the temperature transducer on the entire temperature variation range.

On the temperature interval 1260^0 – 1340^0 are connected the resistances R_2 and R_7;

On the temperature interval 1096^0 – 1216^0 are connected the resistances R_3 and R_7;

On the temperature interval 960^0 – 980^0 are connected the resistances R_4 and R_8;

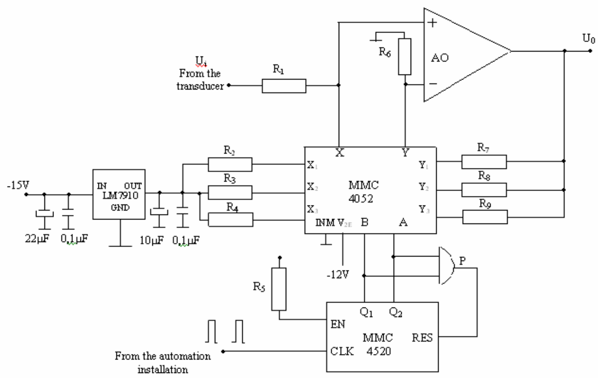


Fig.4 Translation circuit of the values measured in the process

The reference voltage $U_r = -10V$ is imposed to have at the positive input, in case when the steel temperature is at the interval's minimum limit, the voltage $U_i = 0V$.

The switches K_1 and K_2 are achieved with the multiplexor MMC 4052 and the reference voltage with a source LM 7910 (fig. 4).

The diagram is composed by: an operational amplifier (OA) connected as non-inverter summation device (fig. 4),[5] an electronic switch achieved with a multiplexor/de-multiplexor (MMC 4052) and a status counter (MMC 4520).

At the operational amplifier's non-reversing input, by means of rezistance R_1, is brought the analogue voltage supplied by transducer, noted by U_i. On one of the rezistances R_2, R_3 or R_4 is brought also a negative reference voltage $U_r = -10V$, depending on the work range. The determination mode of the rezistance values is presented in the further relations, for each transducer.

The negative reaction is achieved with the rezistive grid R_6 (common for all measuring ranges) R_7, R_8 or R_9 (depending on the range), the latest being introduced in the circuit by means of a multiplexor/de-multiplexor, their value establishing the necessary amplification factor so that, at the maximum weight related to the work range, to obtain at output $U_0 = 10V$.

The MMC 4052 integrated circuit contains two differential analogue multiplexors/de-multiplexors of 4 channels each, controlled by the same address.[12] One of them is used for the summing resistive grid, and the other for the reaction grid.

It's operational description is presented further (table 1).

Table 1

B	A	Input connection	Reaction connection
0	0	$X \to X_0$	$Y \to Y_0$
0	1	$X \to X_1$	$Y \to Y_1$
1	0	$X \to X_2$	$Y \to Y_2$
1	1	$X \to X_3$	$Y \to Y_3$

where by: X_i, Y_i were noted the inputs/outputs, and by X,Y was noted the output/input.

On the address inputs are brought the less significant bits of a 4-bit synchronous binary counter (MMC 4520). This one receives on the tact input an impulse-at-a-time provided either by the automation installation or manually, corresponding to each status, respectively to each selected field. At rest, at the counter's output we have $Q_1=Q_2=0$ and the measuring process is not achieved.

For switching to 1230 ^{0}C…1340 ^{0}C an impulse is applied on the counter's tact input. We'll have $Q_2=0$ şi $Q_1=1$. Are achieved the connections $X \to X_1$ respectively $Y \to Y_1$, in the circuit being introduced the resistances R_2 respectively R_7.

For switching to 1096 ^{0}C…1216 ^{0}C is aplied another tact impulse : $Q_2=1$; $Q_1=0$ and in the circuit are introduced the resistances R_3 and R_8.

Similarly, for switching to 960 ^{0}C…980 ^{0}C, is applied a new impulse on the tact input, $Q_2=1$, $Q_1=1$, are achieved the connections $X \to X_3$ respectively $Y \to Y_3$, being introduced in circuit the resistances R_4 and R_9.

At the next tact impulse, $Q_2=Q_1=0$ and it returns to the initial rest status.

If introduction of a rest status is not desired, will be used the inputs X_0, X_1 and X_2 respectively Y_0, Y_1 and Y_2 and is introduced the SI logical gate, which avoids the achievement of the connections $X \to X_3$, respectively $Y \to Y_3$.

Effectively, the translation of the measured values was made by the relation:

$$Y = Y_1 + \frac{Y_2 - Y_1}{X_2 - X_1}(X - X_1) \text{ where:} \tag{1}$$

Y_1 – minimum limit of the normed field;
Y_2 – maximum limit of the normed field;
X_1 – minimum limit of the real field;
X_2 – maximum limit of the real field;

Dimensioning of the translation circuit from fig. 3 for the temperature transducer.

The voltages at the temperature transducer's output are:

For $T = 900\ ^0C \Rightarrow U_i = 0\ V$

For $T = 960\ ^0C \Rightarrow U_i = 1{,}2\ V$

For $T = 980\ ^0C \Rightarrow U_i = 1{,}6\ V$

For $T = 1096\ ^0C \Rightarrow U_i = 3{,}92\ V$

For $T = 1216\ ^0C \Rightarrow U_i = 6{,}32\ V$

For $T = 1230\ ^0C \Rightarrow U_i = 6{,}6\ V$

For $T = 1340\ ^0C \Rightarrow U_i = 8{,}8\ V$

For $T = 1400\ ^0C \Rightarrow U_i = 10\ V$

a) *field 1230 ^{0}C…1340 ^{0}C*

$$\frac{U_r}{R_2} = \frac{U_i}{R_1} \tag{2}$$

$$R_2 = -\frac{U_r}{U_i\left(1230\ ^0C\right)} R_1 \Rightarrow R_2 = 5\ k\Omega \tag{3}$$

Is chosen $R_2 = 4{,}99\ k\Omega$;

Is determined the potential V_1 for:

$U_i(1340\ ^0C) = 8{,}8V$

$$\begin{cases} V_1 = U_i - I \cdot R_1 \\ I = \dfrac{U_1 - U_r}{R_1 + R_2} \end{cases} \quad (4)$$

$$V_1 = U_i - \frac{U_i - U_r}{R_1 + R_2} \cdot R_1 \quad (5)$$

$$V_1 = \frac{R_2 U_i(1340) + R_1 U_r}{R_1 + R_2} \Rightarrow V_1 = 1{,}316\ V; \quad (6)$$

$$U_0 = \left(\frac{R_7}{R_6} - 1\right) \cdot V_1 \quad (7)$$

$$R_7 = R_6\left(\frac{U_0\left(1340\,^0C\right)}{V_1} - 1\right) \Rightarrow R_7 = 21{,}77\ k\Omega; \quad (8)$$

b) field 1096 ^{0}C...1216 ^{0}C

$$R_3 = -\frac{U_r}{U_i\left(1096\,^0C\right)} R_1 \Rightarrow R_3 = 8{,}418\,k\Omega \quad (9)$$

Is chosen $R_3 \approx 8{,}2\ k\Omega$

$$V_2 = \frac{R_3 U_i\left(1216\,^0C\right) + R_1 U_r}{R_1 + R_3} \Rightarrow V_2 = 1{,}637\ V \quad (10)$$

$$R_8 = R_6\left(\frac{U_0\left(1216\,^0C\right)}{V_2} - 1\right) \Rightarrow R_8 = 16{,}86\,k\Omega \quad (11)$$

Is chosen $R_8 = 16\,k\Omega$ (or in series with a semiadjustable of 1 kΩ).

c) field 960 ^{0}C...980 ^{0}C

$$R_4 = -\frac{U_r}{U_i\left(960\,^0C\right)} R_1 \Rightarrow R_4 = 27{,}49\ k\Omega \quad (12)$$

Is chosen $R_4 = 27\,k\Omega$

$$V_3 = \frac{R_4 U_i\left(980\,^0C\right) + R_1 U_r}{R_1 + R_4} \Rightarrow V_3 = 0{,}337\ V \quad (13)$$

$$R_9 = R_6\left(\frac{U_0\left(980\,^0C\right)}{V_3} - 1\right) \Rightarrow R_9 = 94{,}6\,k\Omega \quad (14)$$

Is chosen $R_9 = 91\,k\Omega$.

2.3 The utilized Fuzzy controller

To determine the controlling characteristics, there were used: Fuzzy controller PIC 16C74, the appropriate software and ADA 3100 data acquisition board (fig. 5).

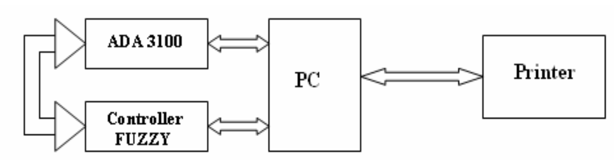


Fig.5

The controller itself was achieved using the microprocessor PIC 16C74, to which were added the necessary hardware circuits. The Fuzzy controller has the following technical characteristics:

- supply voltage: 9 ÷ 16 [Vcc] at connector K4 or 5 [Vcc] at connectors K1, K2;
- 8 analogue inputs, 2 analogue outputs: 0 - 5 [Vcc];
- maximum current at the analogue outputs: 5 [mA];
- direct 8 bit numerical inputs/outputs;
- PWM output: 1,22; 4,88; 19,53 [kHz] at two pins (one mark pin). The impulses are time-modulated (0÷100%);
- inference method: max - min;
- defuzzification by singleton barycentre method;
- tact frequency: 20 [MHz];
- maximum number of rules: 60.
- maximum consumption: 50 [mA];

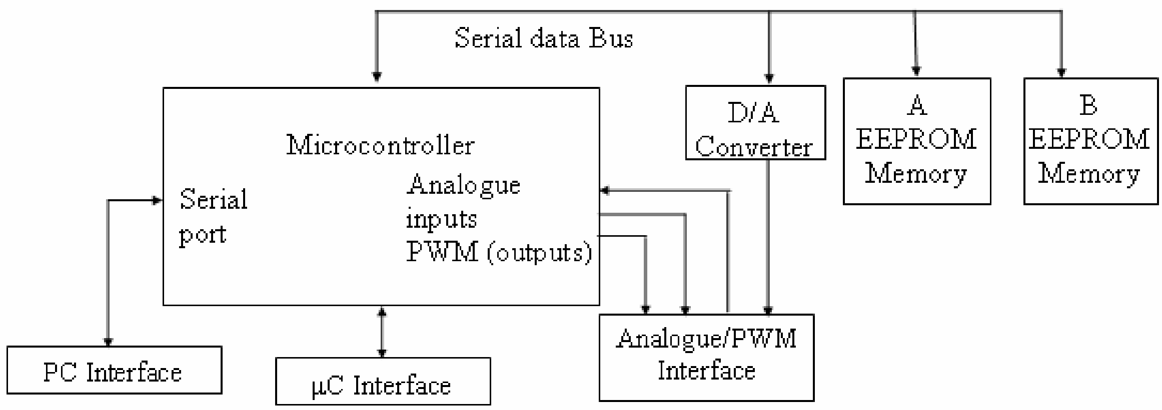


Fig. 6 Fuzzy controller's block diagram

The input/output data can be both analogue and numerical (8 bit), the latest ensuring a much higher transmission speed.

The Fuzzy controller's block diagram (fig. 6) contains a PC necessary only for setting the rules, after which the controller can work independently, directly inside the installation, because all data are memorized into an EEPROM (protected even when disconnecting the power source). The communication with the PC is made through the serial standard interface RS232. The microcontroller PIC 16C74 was purchased as pre-programmed for Fuzzy applications, the necessary instructions for operating as Fuzzy controller being contained in the internal program memory. For introducing the rules, configuring the adjustments, the shape of the appurtenance and simulation functions, was drawn-up a program which is only functional if the Fuzzy controller is connected through the serial interface to the PC.

The controller's software properties are:
- adjustment's control by modifying the input values and observing the output values;
- simulation's graphic display;
- introduction, changing or clearing the rules is anytime possible;
- up to 122 rules and up to 11 appurtenance functions for a linguistic variable;
- logical implications AND/OR;
- free choice of the number of appurtenance functions for each linguistic variable;
- optimization possibilities by introducing a balancing factor for each rule;

For the power supply were provided two versions:
- directly from the system where the controller will be intercalated in (5 [Vcc]);
- strictly independent, case for which it was provided a stabilizing-protection circuit formed by a stabilizer of 5 Vcc (using the circuit 7805).

The connection between the controller and the system's hardware elements is achieved through a connection connector. The connection with other controllers is achieved through another connector that allows to by-pass the convertors A/N and N/A.

The communication is bi-directional and is controlled by $\overline{RD}$, $\overline{WR}$ and $\overline{CS}$. The communication control between controllers is made on the related control lines, and, in order to avoid transmission errors, the delay times between two signals should not be exceeded (fig. 7).

By means of the software, for each analogue input can be chosen a monopolar or bipolar interpretation:
- monopolar: 0÷5 [V] → 0÷100%;
- bipolar: 0 [V] → -100%; 2, 5 [V] → 0%; 5[V] → +100%;

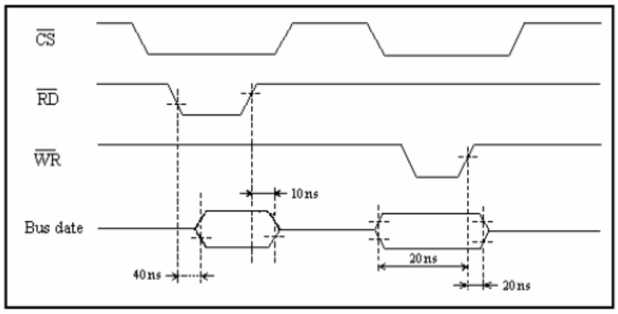


Fig. 7

The user should establish by software if it will be activated the analogue or numerical interface, their simultaneous operation being not possible. The mode in which the controller will receive data and will provide the results is established in the interface's protocol. To achieve a communication, the external controller reads a "communication" byte (table 2) from the Fuzzy controller. Bits 6 and 7 means that the momentary transfer is not possible (e.g. because a data transfer from the PC is taking place). When bit 6 passes in LOW, and 7 in HIGH, it means that the Fuzzy controller is ready to receive data. The bits 0 and 2 of the same byte give in binary form the number of inputs from the regulator A, and the bits 3 and 5 the number of inputs from the regulator B.

Table 2

Bit 7	Bit 0÷6	Configuration
HIGH	bit 0÷2	regulator A inputs number, in binary
HIGH	bit 3÷5	regulator B inputs number, in binary
HIGH	bit 6	LOW - when communication is available; HIGH - in rest.
LOW	bit 0÷2	number of values for the inputs A or B, in binary
LOW	bit 3	without significance, LOW
LOW	bit 4	without significance, LOW
LOW	bit 5	HIGH – when the controller is computing; LOW – when the output is available.
LOW	bit 6	HIGH - when the controller is computing; LOW - when the output is available.

The external controller is reading from the interface until will meet a byte with all the bits 0, situation by which the Fuzzy controller indicates that the transmitted byte was processed and requires to the external controller to transmit the first input value. The cycle is repeating until all the input values of the chosen regulator were transmitted. The reading cycle lasts ≈ 2, 6 μs.

After the introduction of data in the Fuzzy controller is finished, it follows the calculation of the output values that are transmitted to the external controller, by the same protocol.

3 Setting-up the bases of rules for adjusting the cooling water flows

The rated values obtained at the adaptation circuit's output represent the control system's input variables for adjusting the water flows at the secondary cooling in the continuous casting process.

The utilized software has some characteristics:

a) *Inputs and outputs*

It should be set-up the number of inputs, outputs and the utilized interface (analogue or digital). If the analogue interface is chosen, are available two regulators with maximum 8 inputs / regulator.

If the numerical interface is chosen, are available two regulators with maximum 8 inputs and 1 output. The data transmission takes place as serial, on 8 bits. By means of the communication protocol will be established in which way takes place the data exchange.

b) *Appurtenance functions*

After setting-up the inputs, outputs and the interface type, are chosen the appurtenance functions. In this purpose, the program provides an editor (fig.8) by which are selected the domain (unipolar or bipolar), the number and name of the appurtenance functions and their shape. It is possible the automatic generation of the functions' shape and coverage degree.

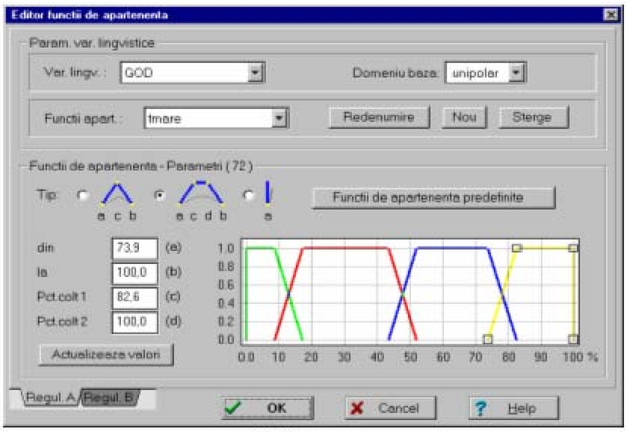


Fig.8

From flexibility reasons, each linguistic value can have up to 11 appurtenance functions, in total being available 86 functions. Each of them is defined as trapeze, triangle or singleton.

Modification of an appurtenance function is made either by direct introduction of other values, or by graphic editing by mouse.

c) *Rules*

After passing through all the previous steps, is appealed the rules editor (fig.9), as table form. The firs row contains the implication "if" - "then", and the second row – the variables' name. In the next rows are introduced the rules themselves. Each is composed by a current number, operator (and/or), the linguistic variables of inputs and outputs and a balancing factor. At value 1 of this factor, the respective rule will not be taken 100% in consideration, at 0, 5 - 50% etc. This facility was introduced in view of a further optimization of the influence of each rule in the system's decision, based on observations from practice.

The base of rules can be modified anytime by the user. Thus, could be added or deleted rules, could be changed the logical operator, regulator A or B.

In the status bar under the table are indicated the active regulator, number of linguistic variables, momentary number of rules.

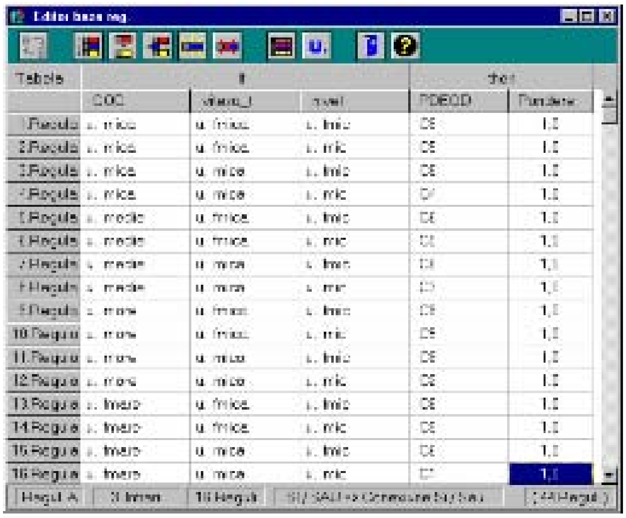


Fig.9

d) *Defuzzification*

It can be achieved by two methods. First is the barycentres method, which represents very well the set, but leads to many mathematical calculations.

The second method – of the singleton barycentres – has similar results, but uses less mathematical calculations. It's recommended for rapid systems, when the computing time is important.

e) *Adjustment's control*

It's used for the regulator's optimization, giving different values for each linguistic input variable and analyzing the behavior of the Fuzzy adjustment in different situations. The calculated values will be graphically delivered, for an easier analysis.

f) *Data delivery*

The change-over of the system's relevant values is done rapidly, so that it can not be observed with the naked eye. From this reason, the program has a menu for graphic display, during or after receiving the signals.

Considering the above, the software properties of

the achieved controller are:
- adjustment's control by modifying the input values and observing the output values;
- simulation's graphic display;
- introduction, changing or clearing the rules is anytime possible;
- up to 122 rules and up to 11 appurtenance functions for a linguistic variable;
- logical implications AND/OR;
- free choice of the number of appurtenance functions for each linguistic variable;
- optimization possibilities by introducing a balancing factor for each rule;

To obtain a better adjustment accuracy, the process was divided in two regimes: start-stop and continuous casting.

For each part was establised the base rules and the membership functions which lead to obtain the controll surfaces and statical characteristics.

Establishment of the rules bases was made depending on the specified temperatures, as well as on the steel's withdrawal speed from the mould (fig. 10).

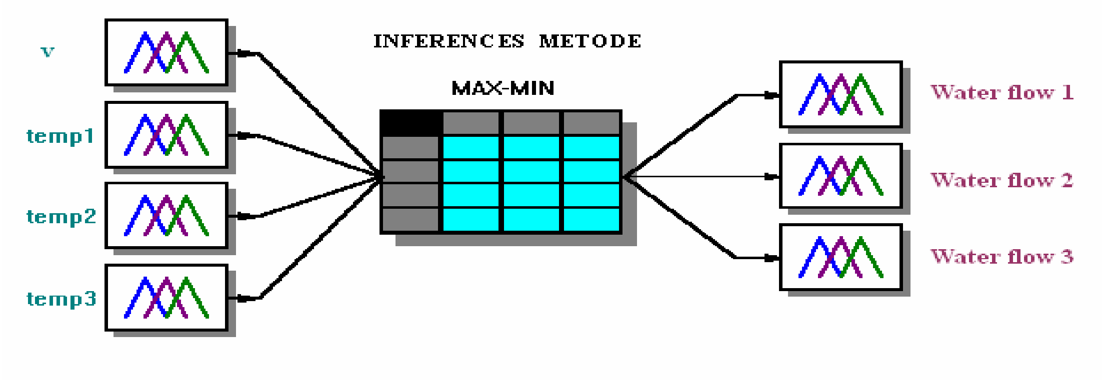


Fig.10 The block diagram of the Fuzzy regulator

After setting-up the input and output measures, there were obtained their appurtenance functions for each regime in part. As example, will be presented the appurtenance functions for the input measures (fig. 11) and for the output measures (fig. 12) corresponding to the start-stop regime.

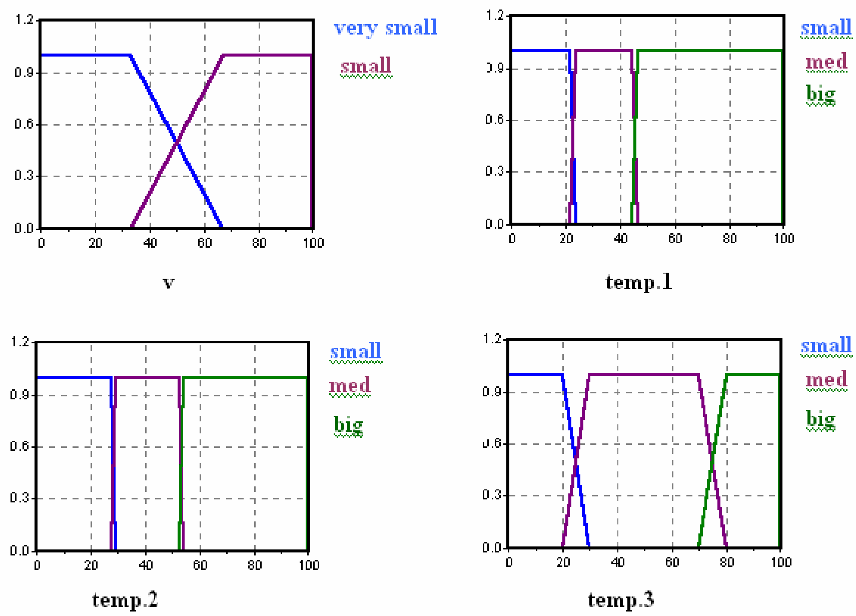


Fig.11 Appurtenance functions of the input variables

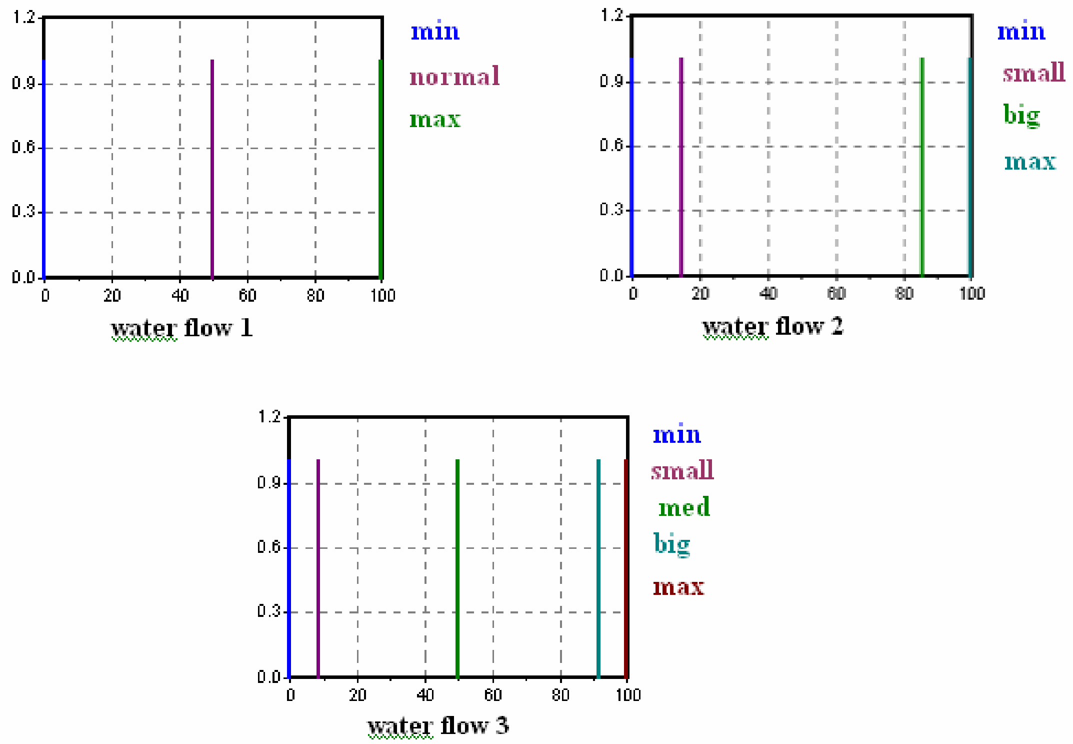


Fig.12 Appurtenance functions of the output variables

Based on the appurtenance functions, there were established the bases of rules for each regime in part. These contain a number of 54 rules for the start-stop regime and 54 rules for the continuous casting process.

Considering the great data volume, is presenting a restrained number of rules specific to the start-stop regime (table3).

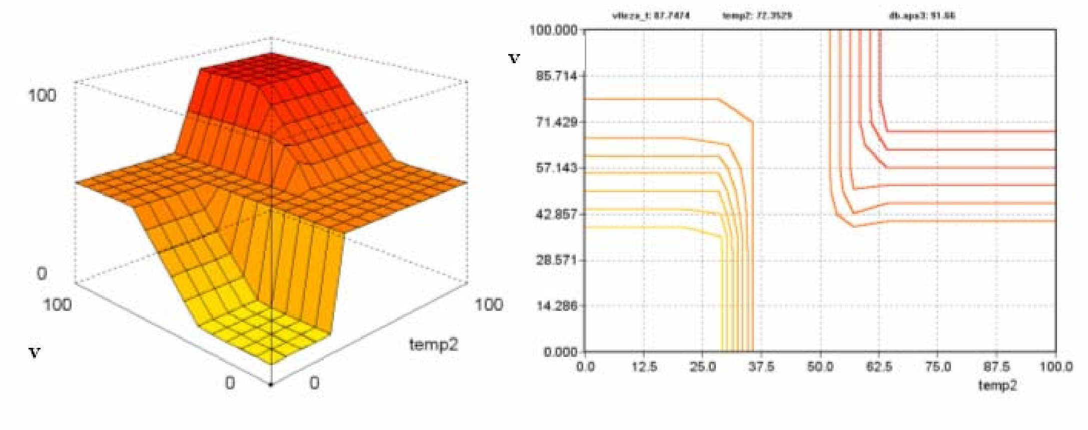
Table 3

IF v = very small AND temp 1 = small AND temp 2 = small AND temp 3 = small THAN water flow 1 = min AND water flow 2 = min AND water flow 3 = min (100%)
IF v = very small AND temp 1 = small AND temp 2 = small AND temp 3 = med THAN water flow 1 = min AND water flow 2 = min AND water flow 3 = small (100%)
IF v = very small AND temp 1 = small AND temp 2 = small AND temp 3 = big THAN water flow 1 = min AND water flow 2 = min AND water flow 3 = med (100%)
IF v = very small AND temp 1 = small AND temp 2 = med AND temp 3 = small THAN water flow 1 = min AND water flow 2 = small AND water flow 3 = small (100%)
IF v = very small AND temp 1 = small AND temp 2 = med AND temp 3 = med THAN water flow 1 = min AND water flow 2 = small AND water flow 3 = med (100%)
IF v = very small AND temp 1 = small AND temp 2 = med AND temp 3 = big THAN water flow 1 = min AND water flow 2 = small AND water flow 3 = big (100%)
IF v = very small AND temp 1 = small AND temp 2 = big AND temp 3 = small THAN water flow 1 = min AND water flow 2 = big AND water flow 3 = small (100%)
IF v = very small AND temp 1 = small AND temp 2 = big AND temp 3 = med THAN water flow 1 = min AND water flow 2 = big AND water flow 3 = med (100%)

Based on the appurtenance functions and the bases of rules, there were obtained the adjustment surfaces and the static characteristics.

One of the adjustment surfaces and static characteristics obtained experimentally according to the diagram from fig. 5 is presented in fig. 13. This characteristic corresponds the case where it was represented the cooling water flow in zone 3 depending on the withdrawal speed and temperature in zone 2, for the situation when the temperature in zone 1 is medium and the temperature in zone 3 is medium.

From the analysis of all surfaces, it was found that there are no discontinuities and that they correspond to all the possible situations comprised in the bases of rules.



a)
adjustment surface

b)
static characteristic

Fig.13
Water flow 3=f (v, temp 2)
temp 1 – med, temp 3 – med

4 Conclusion

The proposed adaption system achieves a linear translation of the output measures from the transducers to the Fuzzy regulator on the entire variation range, both of the temperature domain and the withdrawal speed's.

Considering the differences that appear in the continuous casting process to ensure a precision as better possible of the adjustment, this was splitted in two regimes: the start-stop regime and the continuous casting regime itself.

Depending on the values of the input measures and the necessity to obtain some values for the output measures that should ensure a superior quality of the cast product, there were established the appurtenance functions and bases of rules for each regime in part. Based on these, there were obtained experimentally the adjustment surfaces and the static characteristics corresponding to each situation comprised in the bases of rules.

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