Applications of fuzzy logic in continuous casting

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Abstract: - In the process of continuous casting, the melted steel from the melting pot is passed, through the intermediary of the distributor, in the water-cooled crystallizer tank. In this way, a crust forms here which is solidified at the exterior, and one of the great problems is its cracking or even it's tearing, due to several factors. Our paper describes a new control method we should use during the continuous casting. This method is based on the fuzzy logic, in order to avoid any crack inside the crystallizing apparatus. This method contains two fuzzy controllers which, based on a set of rules established with the help of the mathematical model to the crust solidification process of the semi-product inside the crystallizing apparatus and uses the experience of human experts, requires changes of the casting speed value and the primary cooling water flow.

Key-Words: - fuzzy logic, base of rules, membership functions, control system, continuous casting

1 Introduction

In the process of continuous casting, the melted steel from the melting pot is passed, through the intermediary of the distributor, in the water-cooled crystallizer tank. In this way, a crust forms here which is solidified at the exterior, and one of the great problems is its cracking or even its tearing, due to several factors [4]. When the portion that has suffered the crack gets out of the crystallizing apparatus, the cast iron pours out and the casting process must be stopped. Such an accident must be avoided by detecting all cracks and reducing the casting speed or increasing the primary cooling water flow, allowing the iron to become solid [9], [10].

Figure no. 1 describes the steel continuous casting equipment.

The elements which make the continuous casting equipment are described based on how they happen during the elaboration process of continuous cast steel. They are: the cast device, the distributor, the crystallizing apparatus, and the oscillometre; the secondary cooling off area; the exaggeration and straightening area; the start beam; the aggregate for semi-products yielding.

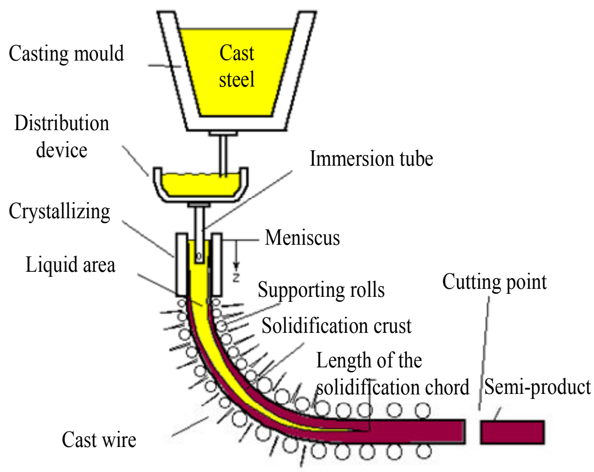


Fig. 1. Steel continuous casting equipment

In [9] is described the structure of the crack detection systems. Such cracks may occur during the continuous casting process, especially of those who are based on a neuronal network [13]. This network makes a „1"-logical output signal when it detects a primary crack of the crystallizing apparatus; otherwise it produces a „0"- output signal. This information should be used properly in order to avoid any possible crack before the material exits the crystallizing apparatus [11].

Since the current installations can not do that, in this paper we propose a fuzzy solution which could be added to the current structure of the control system of the continuous casting. Besides that, it uses all the features of the fuzzy logic[1],[2],[4] and it is able to predict any possible crack[5], providing with the best solutions and actions in order to prevent any cracks inside the crystallizing apparatus.

We could use this structure for any type of installation of continuous casting, but only along with the neuronal network for primary crack detection [9],[10]. Thus, considering the prediction principle we have chosen, we believe we are able to eliminate any fault during the casting process, when the cast material has cracks when coming out of the crystallizing apparatus [6].

2 The Structure of the Control System of the Continuous Casting

In Fig. no. 2 we describe the modern pattern of the control system of the continuous casting. The red line points out the change we have done. We mention that these changes are only additional, meanwhile the old system works with or without them. This principle widens the area of using this solution.

Fig.2 describes the two fuzzy controllers [7] we have proposed:

a) FC0 – it turns active when the neuronal network [9] has not yet detected any primary cracks inside the crystallizing apparatus. It analyses the four input sizes: the current casting speed, the current flow of the primary cooling water, the temperature inside the distributor, and the technological risk. Based on these information and on a set of rules we are going to manage some changes of the casting speed and of the cooling water flow in order to avoid any cracks.

b) FC1 – it turns active when the neuronal network has already detected some cracks in material inside the crystallizing apparatus. Based on three input sizes - the current casting speed, the current flow of the primary cooling water and the real temperature inside the distributor - this device enables significant changes of the casting speed and of the cooling water in order to avoid any crack. the set of rules we use differs from the FC0 set. The technological risk should not be considered because the crack has already occurred.

Referring to this structure, we should point out the following details:

- technological risk refers to certain details who have been established by experts. Experts consider that any crack may or may not be caused by the chemical components of the steel. In order to establish the exact value of the technological risk, we have drawn up this paperwork after we had consulted some experts. The mathematical model of the solidification process [5] has also allowed us to get some important conclusions about the technological risk of crack occurrence.

- both controllers cause an output variation (percentage) of the cooling water flow and of the casting speed. Their outputs shall be summed up and used for a correction block for that particular size - it works according to the relation:

- for speed:

$$v_c = \left(1 - p_v\right) \cdot v^* \qquad (1)$$

where: $p_v = \dfrac{\Delta v}{100}$ is the controller's output;

v^* - the value of the speed, while it is not corrected.

- for the flow:

$$q_c = \left(1 + p_q\right) \cdot q^* \qquad (2)$$

where: $p_q = \dfrac{\Delta q}{100}$ is the controller's output;

q^* - required flow value, while it has not been corrected yet.

- the two controllers shall work alternatively[7],[8] according to the output size of the neuronal network for any crack detection.

- FC0 has 225 rules, meanwhile FC1 has 75 rules. It has been a real effort to analyze all possible cases. For that matter, we have contacted a number of experts with a lot of experience of using continuous casting equipments. We have analyzed each case in particular, in order to establish the phenomenon of crust solidification according to the mathematical model [5]. Of course, the set of rules is far from being perfect, since it is influenced by a lot factors who consider the state of the equipments and any other practical features. This pattern is going to be improved while working and testing the pattern we have proposed, like in case of any other expert systems.

- due to the original and novelty features of the principle and of the crack elimination equipment structure (during the continuous casting), it has not been completely implemented yet (for this particular industrial domain). We have checked them up during several experiments in order to come up with the best decision about the two controllers. These experiments have confirmed that the methods are faultless.

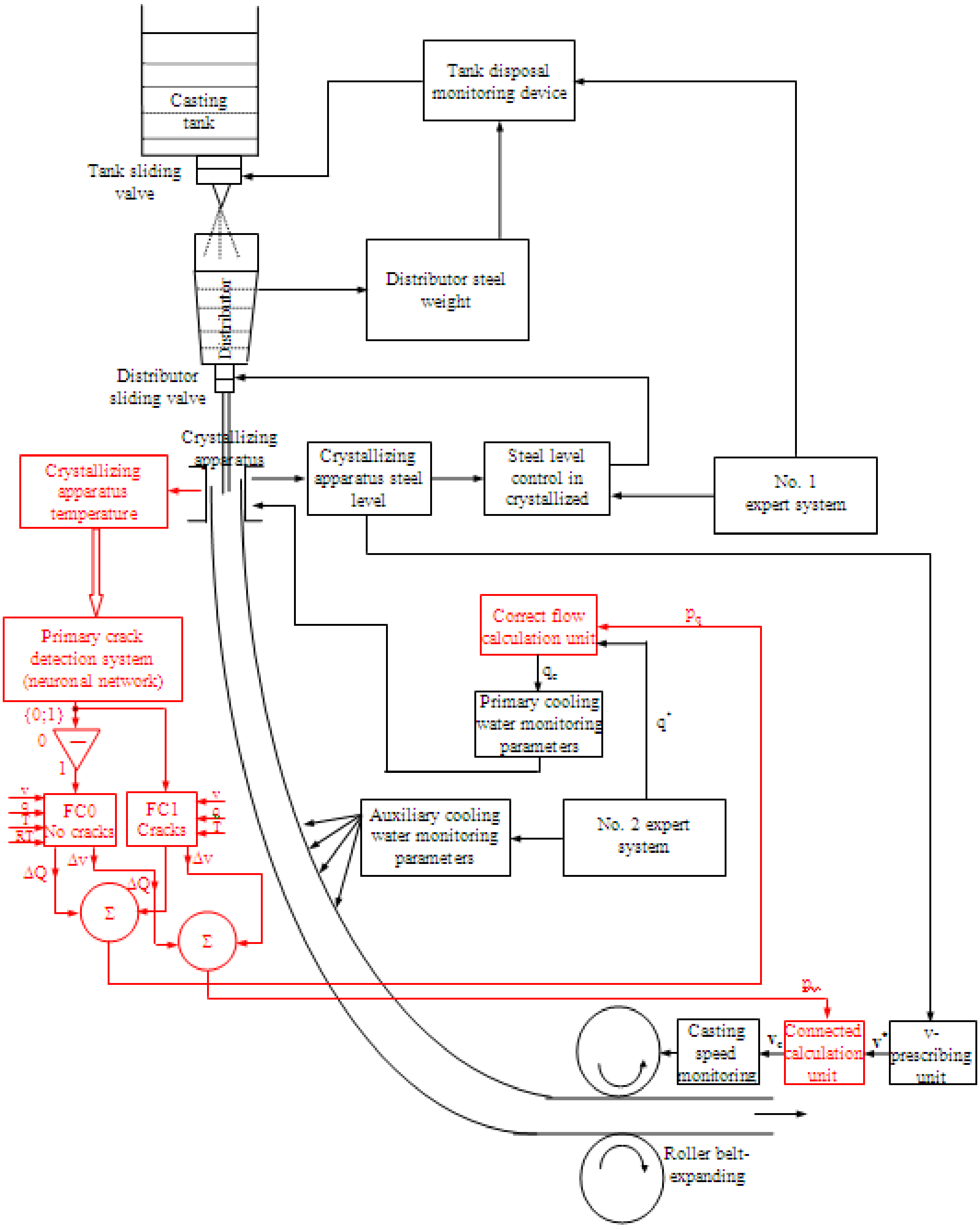


Fig.2 The structure of the control system of the continuous casting

- the complete implementation of this method needs important amounts of money and it may stop the working of the equipment for a while. That is difficult nowadays (all equipments of continuous casting are owned by private companies and they belong to a technological process – downstream split process). If we stop them they disable the finite goods production and cause important economic loss. We recommend you to implement this method for any new equipment or to improve the old ones.

3 Fuzzy controllers to eliminate cracks in continuous casting

3.1 Design of fuzzy controller FC0

We have designed the CF0 fuzzy controller, we have established the linguistic terms (for both input and output), the membership functions, and the set of rules that we use for obtaining the control surfaces, with the help of the Matlab simulation.

In figure 3 we describe the block diagram of the fuzzy controller FC0.

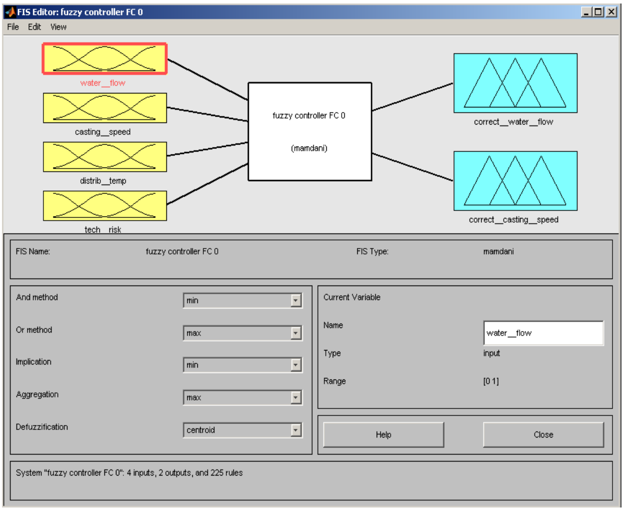


Fig. 3 Block diagram of the fuzzy controller FC0

Input information

1) water _ flow (water flow in crystallizing apparatus, [l/min])

Number of states: 5

States	Real domain [l/min]	Standardized values domain
Very small	900 ÷ 940	0÷0,2
Small	940 ÷ 980	0,2÷0,4
Medium	980 ÷ 1020	0,4÷0,6
Big	1020 ÷ 1060	0,6÷0,8
Very big	1060 ÷ 1100	0,8÷1

2) casting_ speed (casting_ speed, [m/min])

Number of states: 5

States	Real domain [m/min]	Standardized values domain
Very small	0,7 ÷ 0,8	0÷0,2
Small	0,8 ÷ 0,9	0,2÷0,4
Medium	0,9 ÷ 1,0	0,4÷0,6
Big	1,0 ÷ 1,1	0,6÷0,8
Very big	1,1 ÷ 1,2	0,8÷1

3) distributor _ temperature (steel temperature in crystallizing apparatus [°C])

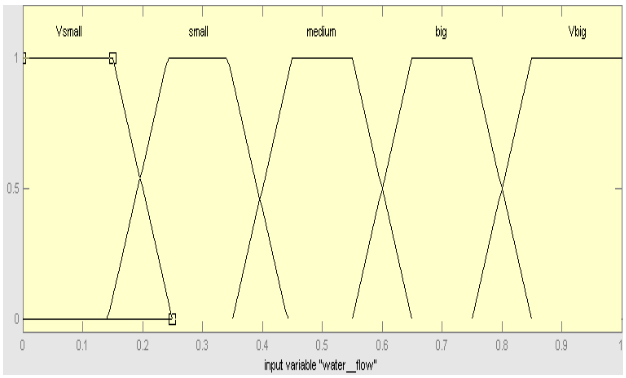
Number of states: 3

States	Real domain [°C]	Standardized values domain
Small	1540 ÷ 1550	0÷0,33
Medium	1550 ÷ 1560	0,33÷0,66
Big	1560 ÷ 1570	0,66÷1

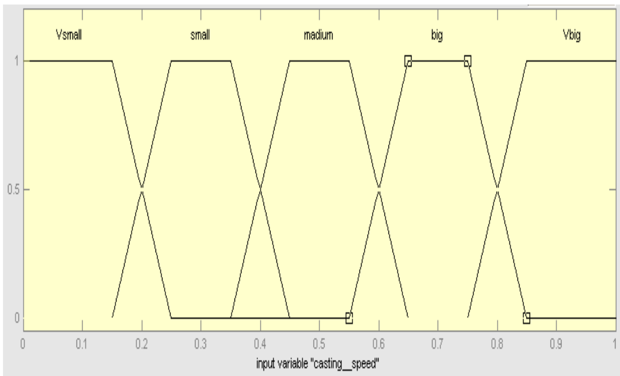
4) Technological risk [%]

Number of states: 3

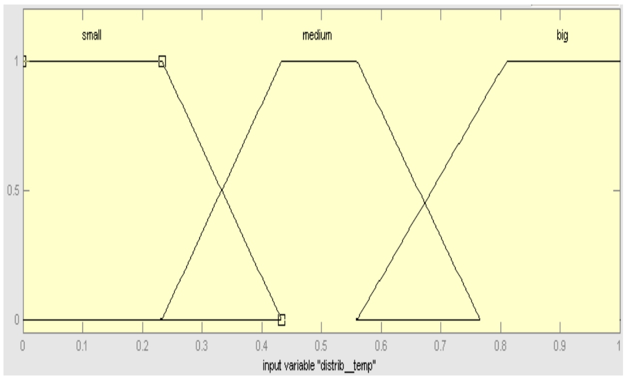
States	Real domain [%]	Standardized values domain
Small	0÷20	0÷0,33
Medium	20÷40	0,33÷0,66
Big	40÷60	0,66÷1



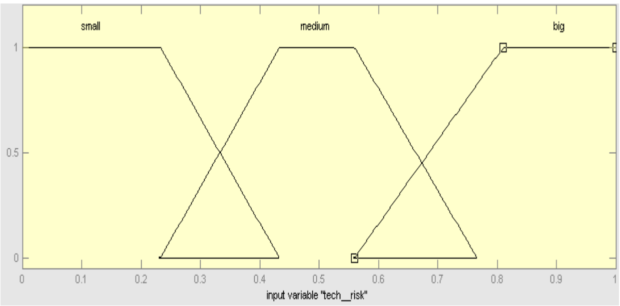
a) Membership function „water _flow”



b) Membership function „casting _speed”



c) Membership function „distrib _temp”



d) Membership function „tech _risk"

In figures a, b, c, and d we describe the membership functions for the input sizes.

Output information

1) correct_water_flow (water flow corection [l/min])

Number of states: 5

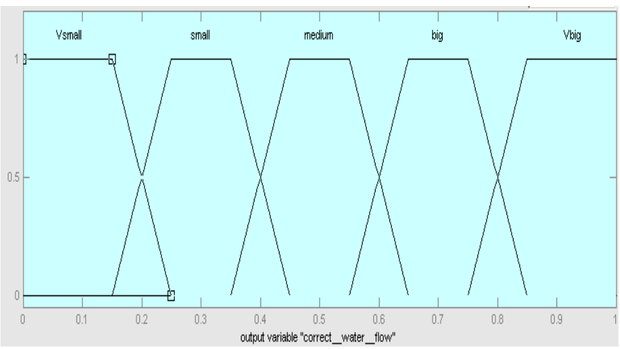
States	Real domain [%]	Standardized values domain
Very small	0÷4	0÷0,2
Small	4÷8	0,2÷0,4
Medium	8÷12	0,4÷0,6
Big	12÷16	0,6÷0,8
Very big	16÷20	0,8÷1

2) correct_casting_speed(casting speed correction [m/min])

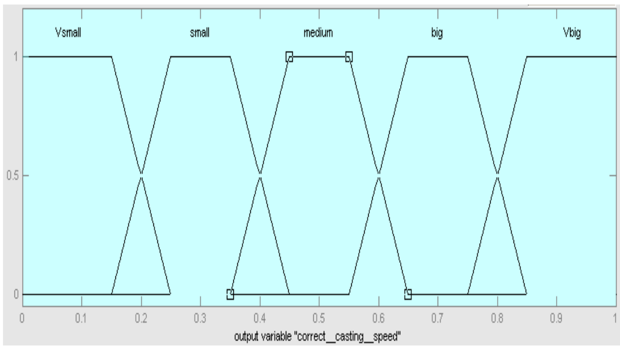
Number of states: 5

States	Real domain [%]	Standardized values domain
Very small	0÷-4	0÷0,2
Small	-4÷-8	0,2÷0,4
Medium	-8÷-12	0,4÷0,6
Big	-12÷-16	0,6÷0,8
Very big	-16÷-20	0,8÷1

In figures e, f we describe the membership functions for the output sizes.



e) Membership function „correct _ water _flow"



f) Membership function „ correct _ casting _ speed"

Table of inference for some of the rules is given below:

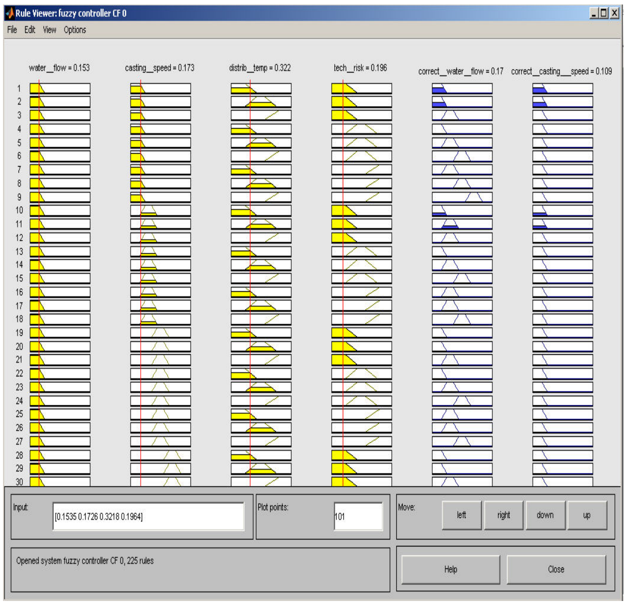


Fig. 4 Table of inference for FC0

Control surfaces obtained by simulations according to the block diagram from the figure 5 are listed below:

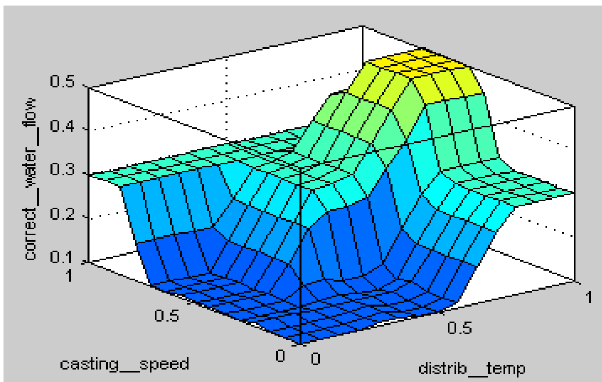


Fig.5 Control surface

Correct _water _flow=f (distrib _temp, casting _speed) at water _flow=const. and tech_ risk=const.

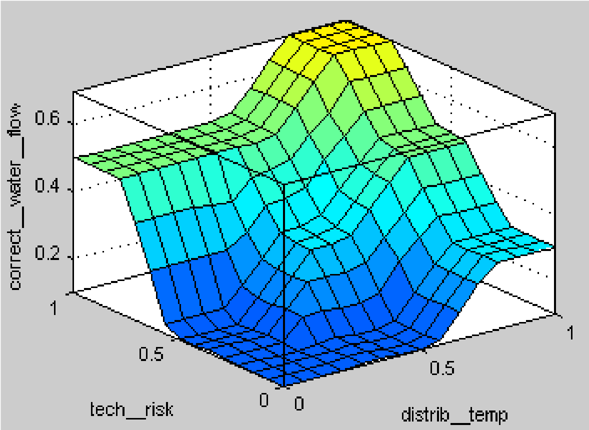


Fig.6 Control surface
Correct _water _flow=f (distrib _temp, tech _risk) at water _flow=const. and casting _speed=const.

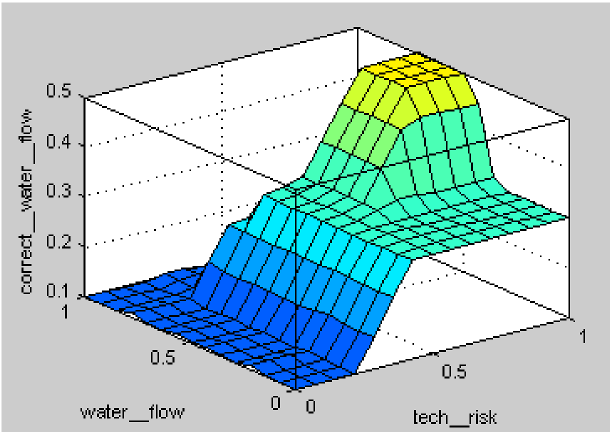


Fig.7 Control surface
Correct _water _flow=f (tech _risk, water _flow) at casting _speed=const. and distrib _temp=const.

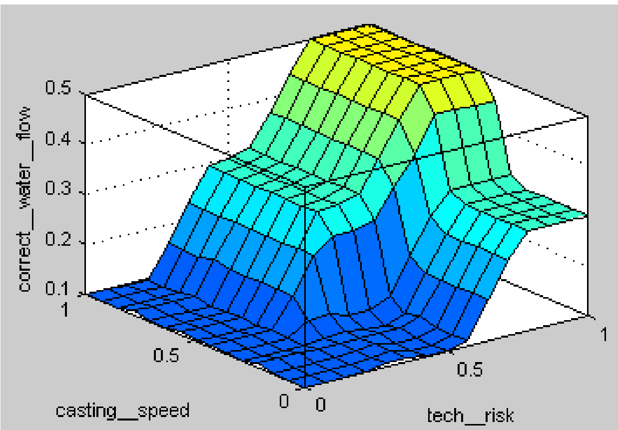


Fig.8 Control surface
Correct _water _flow=f (tech _risk, casting _speed) at water _flow=const. and distrib _temp =const.

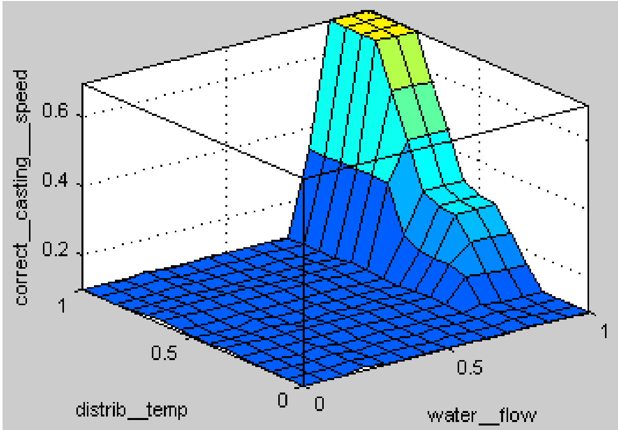


Fig.9 Control surface
Correct _casting _speed=f (water _flow, distrib _temp) at casting _speed=const. and tech _risk =const.

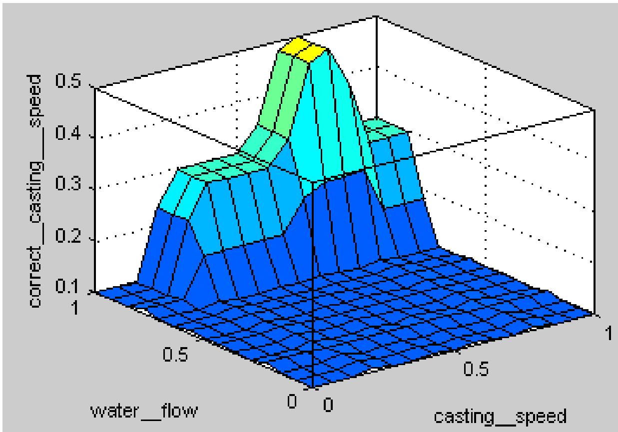


Fig.10 Control surface
Correct _casting _speed=f (casting _speed, water _flow) at distrib _temp=const. and tech _risk =const.

3.2 Design of fuzzy controller FC1

In figure 11 we describe the block diagram of the fuzzy controller FC1.

Input information's

1) water _ flow (water flow in crystallizing apparatus, [l/min])

Number of states: 5

States	Real domain [l/min]	Standardized values domain
Very small	900 ÷ 940	0÷0,2
Small	940 ÷ 980	0,2÷0,4
Medium	980 ÷ 1020	0,4÷0,6
Big	1020 ÷ 1060	0,6÷0,8
Very big	1060 ÷ 1100	0,8÷1

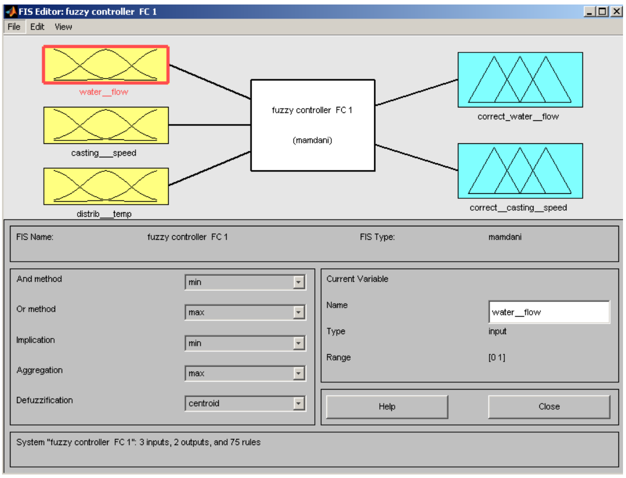


Fig. 11 Block diagram of the fuzzy controller FC1

2) casting _speed (casting_speed, [m/min])

Number of states: 5

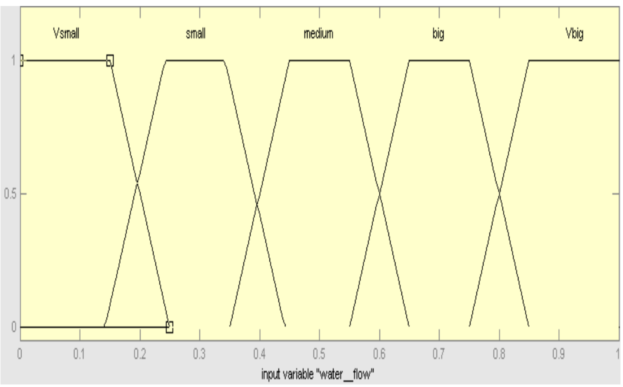
States	Real domain [m/min]	Standardized values domain
Very small	0,7 ÷ 0,8	0÷0,2
Small	0,8 ÷ 0,9	0,2÷0,4
Medium	0,9 ÷ 1,0	0,4÷0,6
Big	1,0 ÷ 1,1	0,6÷0,8
Very big	1,1 ÷ 1,2	0,8÷1

3) distributor _ temperature (steel temperature in crystallizing apparatus [°C])

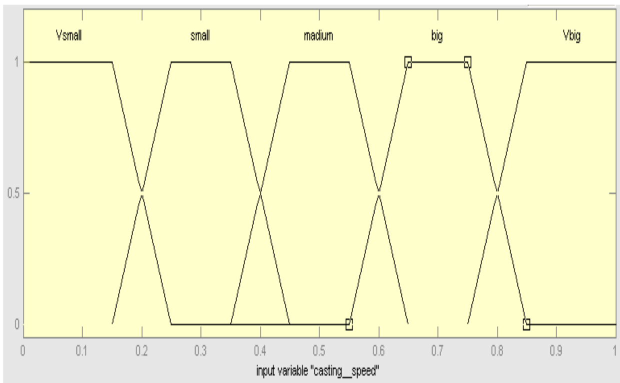
Number of states: 3

States	Real domain [^{0}C]	Standardized values domain
Small	1540 ÷ 1550	0÷0,33
Medium	1550 ÷ 1560	0,33÷0,66
Big	1560 ÷ 1570	0,66÷1

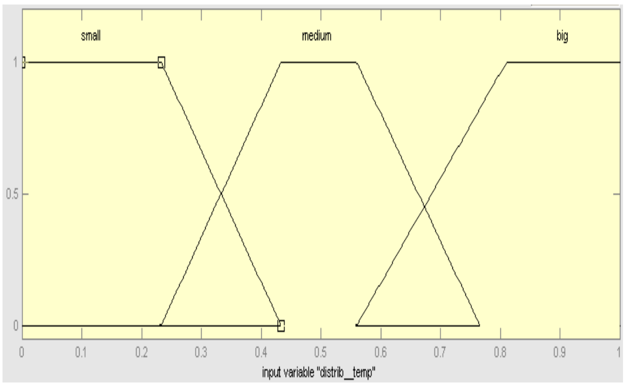
In figures g, h and i we describe the membership functions for the input sizes.



g) Membership function „water _flow"



h) Membership function „casting _speed"



i) Membership function „distrib _temp"

Output information's

1)correct_water_flow (water flow corection [l/min])

Number of states: 5

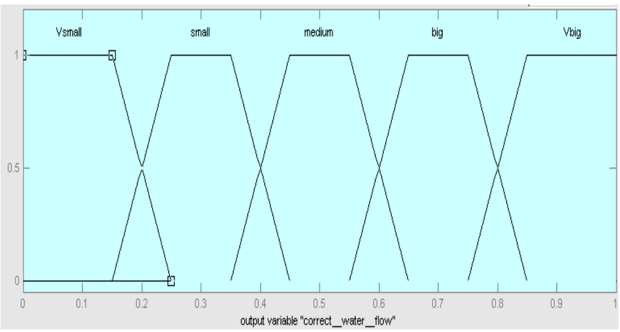
States	Real domain [%]	Standardized values domain
Very small	0÷-4	0÷0,2
Small	-4÷-8	0,2÷0,4
Medium	-8÷-12	0,4÷0,6
Big	-12÷-16	0,6÷0,8
Very big	-16÷-20	0,8÷1

2) correct_casting_speed(casting speed correction [m/min])

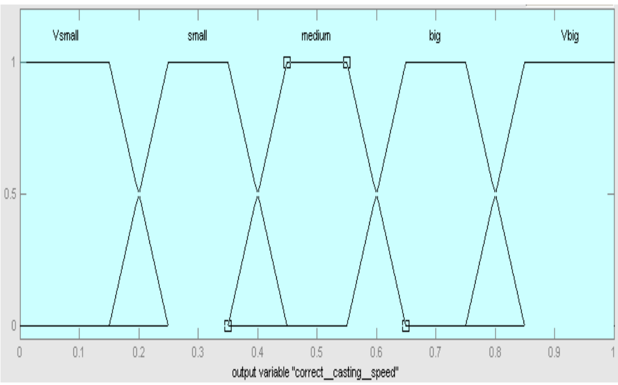
Number of states: 5

States	Real domain [%]	Standardized values domain
Very small	0÷-4	0÷0,2
Small	-4÷-8	0,2÷0,4
Medium	-8÷-12	0,4÷0,6
Big	-12÷-16	0,6÷0,8
Very big	-16÷-20	0,8÷1

In figures j and k we describe the membership functions for the output sizes.



j) Membership function „correct _ water _flow”



k) Membership function „ correct _ casting _ speed”

Table of inference for some of the rules is given below:

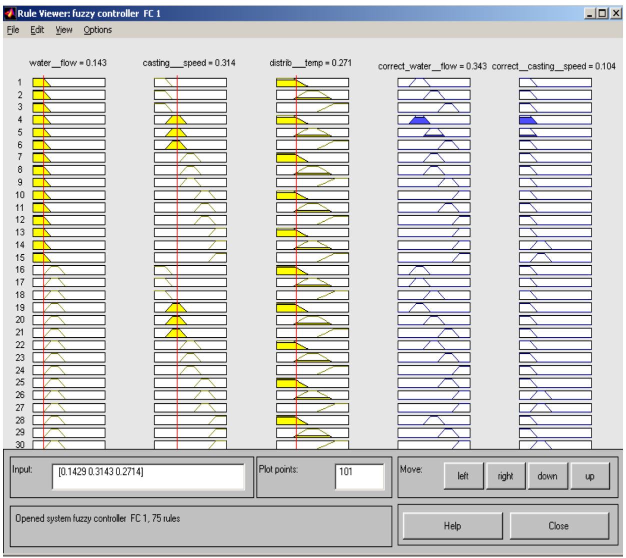


Fig. 12 Table of inference for FC1

Control surfaces obtained by simulations according to the block diagram from the figure 11 are listed below:

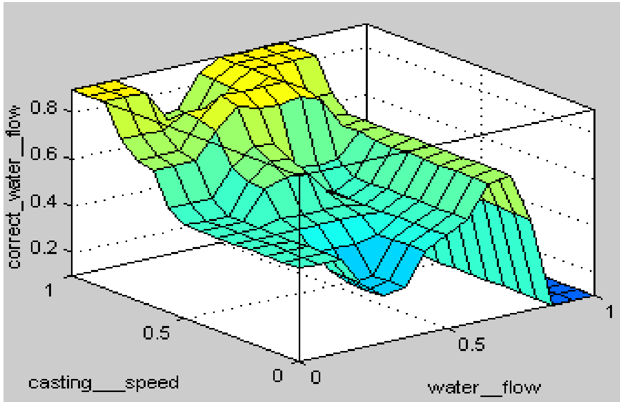


Fig.13 Control surface
Correct_water_flow=f (water_flow, casting_speed)
distrib _temp=const.

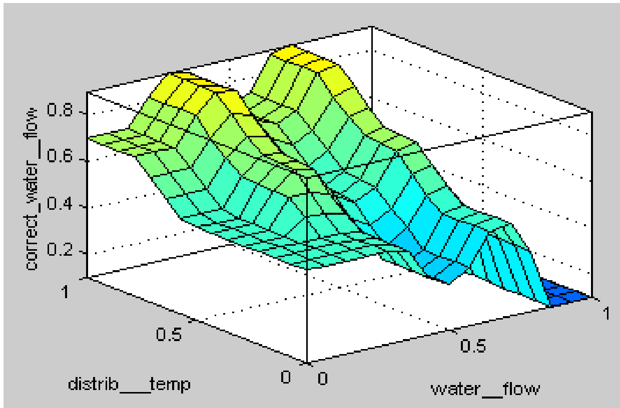


Fig.14 Control surface
Correct_water_flow=f (water_flow, distrib _temp)
casting _speed=const.

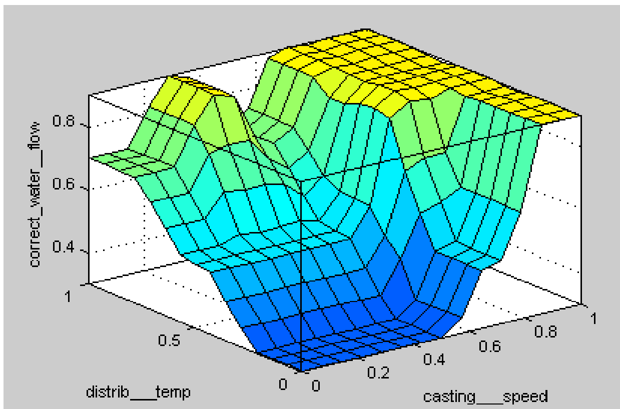


Fig.15 Control surface
Correct_water_flow=f (casting_speed, distrib_temp)
water_flow=const.

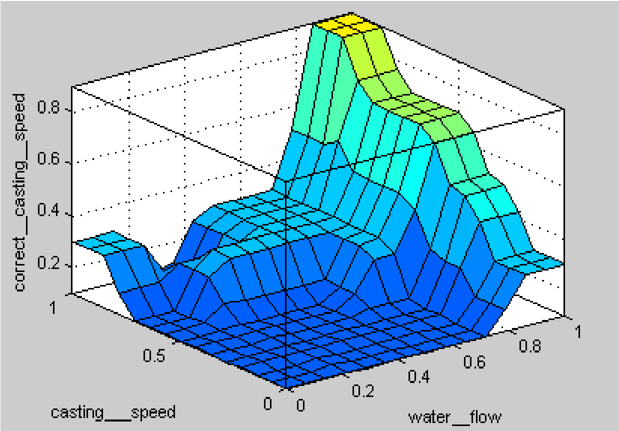


Fig.16 Control surface Correct_casting_speed=f (water_flow, casting_speed) distrib _temp=const.

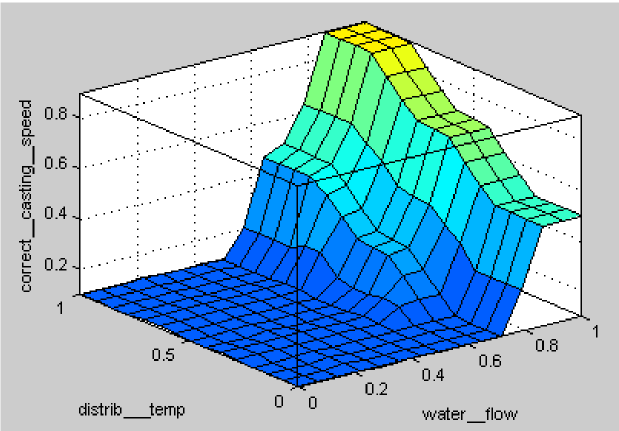


Fig.17 Control surface Correct_casting_speed=f (water_flow, distrib_temp) casting_speed=const.

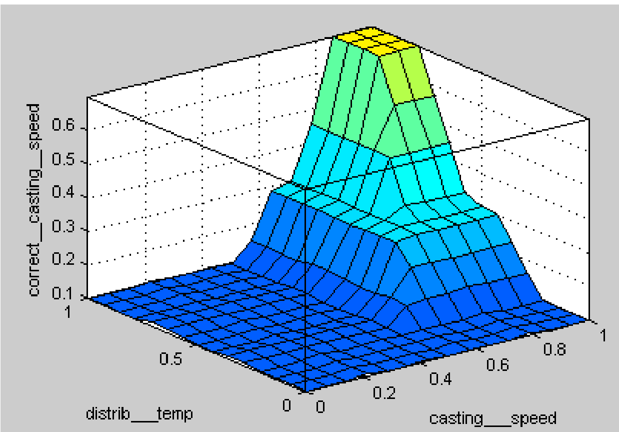


Fig.18 Control surface Correct_casting_speed=f(casting_speed, distrib_temp) water_flow=const.

4 Conclusions

This paperwork describes a modern control method we should use during the continuous casting. This method is based on the fuzzy logic, in order to avoid any crack inside the crystallizing apparatus. This method contains two fuzzy controllers FC0 and FC1 which, based on a set of rules established with the help of the mathematical model to the crust solidification process of the semi-product inside the crystallizing apparatus and uses the experience of human experts, requires changes of the casting speed value and the primary cooling water flow.

When we have designed the pattern, we considered other important features: it should anticipate any crack, which allows us to take some measures in order to diminish the number of cracks inside the crystallizing apparatus, without decreasing the productivity of the equipment; once the primary cracks have been detected by the neuronal network, another controller consider this situation and take the most appropriate measures in order to avoid the temporarily decrease of the productivity; the pattern should be as flexible as possible, in order to adjust to any equipment we already use. This is possible if we change the set of rules, and does not imply any additional costs.

Although, the pattern has not yet been practically used, a part of the set of rules has been implemented and tested for an industrial equipment. It has uphold that the data is correct.

We consider that any costs could be paid off within a year, by elliminating casting waste.

References:

[1] Bouhouche S., Lahreche M., Moussaoui A. and Bast J., Quality Monitoring Using Principal Component Analysis and Fuzzy Logic. Application in Continuous Casting Process, American Journal of Applied Science (AJAS), 4(9),, ISSN: 1546-9239, 2007, pp.637-644.

[2] Drainkov, D., Hellendoom, H., Reinfrank,M. ,An Introduction to Fuzzy Control, *Springer-Verlag*, Berlin, 1993.

[3] Lagrat I, El Ougli A , Boumhidi I, Optimal Adaptive Fuzzy Control for a Class of Unknown Nonlinear Systems, *WSEAS TRANSACTIONS on SYSTEMS and CONTROL*, Issue 2, Volume 3, February 2008, ISSN: 1991-8763, pp.89-98.

[4] Lee, C. C., Fuzzy logic in control systems: Fuzzy logic controller, *IEEE Trans. Systems, Man & Cybernetics* 20(2): 404-435, 1990.

[5] Li, C., Thermo-mechanical finite element model of shell behaviour in the continuous casting of steel, *Sixth Asia-Pacific Symposium on Engineering Plasticity and its Applications*, 2-6 December, Sydney, Australia, 2002.

[6] Nakamura T., Kazuho K., Breakout prediction system in a continuous casting process, *United States Patent*, No.5, 548,520, Date of Patent 20 aug.1996.

[7] Precup, R.E & Preitl, Șt., *Fuzzy Controllers*, Editure Academic Horizons, ISBN: 973-9400-61-2, Timişoara, Romania, 1999.

[8] Singh J., Ganesh A., Design and Analysis of GA based Neural/Fuzzy Optimum Adaptive *Control, WSEAS TRANSACTIONS on SYSTEMS and CONTROL*, Issue 5, Volume 3, ISSN: 1991-8763, 2008.

[9] Tirian G.O., Neural system for detecting craks in the wire of the continuous casting" *12th International Research/Expert Conference ″Trends in the Development of Machinery and Associated Technology TMT 2008*, Istambul, Turcia, 26 – 30 august, 2008, pp. 649-652.

[10] Tirian G.O., Pinca-Bretotean C., Software implementation of a neuronal system which enabled the prediction of the wire breaking during continuous casting , *Proceedings of the 7th WSEAS International Conference on Circuits, Electronics, Control and Signal Processing*, Tenerife, Spania, December 15-17, 2008, pp.151-156.

[11] Tirian G.O., Rusu-Anghel S., Pănoiu M., Pinca-Bretotean C., Control of the continuous casting process using neural networks, *Proceedings of the 13th WSEAS International. Conference on Computers* , Rodos Island, Greece, July 23-25, ISSN:1790-5109, ISBN:978-960-474-099-4, 2009, pp.199-204.

[12] Tirian G.O., Pinca-Bretotean C., Applications of neural networks in continuous casting , WSEAS TRANSACTIONS on SYSTEMS, Issue 6, Volume 8, June 2009, ISSN: 1109-2777, pp.693-702.

[13] C. Volosencu, *Sisteme fuzzy si neuronale*, Editura Politehnica, Timisoara, 2007.