# MATHEMATICAL MODELLING OF STEEL CONTINUOUS CASTING HYDRODYNAMICS (1)

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## ABSTRACT

*The quality increase of steel continuous casting and a reliability indices of afferent installations imposes the automation systems adoption of machines of continuous casting of steel.*

*In this paper enters original solution of automatic settlement of liquid steel debit and level in tundish and analyses the behaviour in dynamics behaviour of automatic installation.*

KEYWORDS: steel continuous casting, automatization, tundish, mathematical modeling, sliding gate mechanism

## 1. Introduction

The quality increase of steel continuous casting and of afferent installations reliability indices imposes the automation systems adoption of machines of continuous casting of steel. In the framework of those systems, automatic settlement curl of level in tundish has an particular important, as conditions, in good measure, the correct running, under technological aspect of continuous casting machine.

The manual casting management purpose permanent supervision of steel level, process which trains nervous blood-pressure and a growing weariness of operator, which it generates rigging bugs and spoilages of continuous casting installations.

A level too heaved in tundish can turn out overrunning in overflow vein and a level too allows carry forword dross in mould, turning out the line punch. It results, therefore, the automatic settlement necessity of liquid steel level in tundish, for the increase yield of metal, the quality improvement slab and the incidences avoidance of casting, which manage to the machines productivity decrease of continuous casting.

The spatial mechanism for closing with case represents an element of automatic settlement system of level in tundish [2]. In the ones what follow enter an original solution of automatic settlement of level in tundish and analyses the behaviour in dynamic behaviour of automatic installation.

## 2. The automatic settlement algorithm of liquid steel level in tundish

To the automatic settlement system adoption pushed along from realization requirement to a reliable mechanism, taking account of running highly the heavy conditions of this.

The use of a settlement system with continue action should lead a practically permanent running of element execution, which it holds the spatial mechanism, resulting a pronounced wear of this.

The basic idea of proposed system consists in running behaviour relief of execution mechanism, what it works in environmental highly heavy conditions (mechanical and thermic various), demand by the adequate adoption of electric system command, which it works in running pars.

This idea managed to the adoption to a settlement system with sampling. Sampling period, T, it adopted equal to 10 s.

At a some discrete value of time kT, (k = 0, 1, 2, ….), it does the next processes what compare the reaction purveyed signal of transducer, with the reference signal; if the resulted error in absolute value, it surpasses a imposed limit, it the short period displacement command with a assignment quantity, of container case of casting, in a different meaning, contingent on the error mark; if the error is smaller than imposed limit, the mechanism is not acted. Between the sampling periods, the mechanism stands able of rest.

From the ones featured result as proposed algorithm frames in settlement tripozitional systems class with sampling. As it showed, the essential advantage of solution consists in the insurance to a time how smaller of call of acting mechanism. Though it should utilize a proportional command, the sampling adoption lowers with 80% acting time of mechanism. The tripozitional command used in proposed draft, spliced with the signal sampling, it lowers the acting time in a bigger proportion.

Tenet draft of settlement system of liquid steel level in tundish is given in figure 1, in which: 1 is pressure traductor, 2 – hydraulic drum, 3 – tundish, 4 – command element by impulses (with sampling), 5 – execution element, 6 – closing appliance with sliding case.

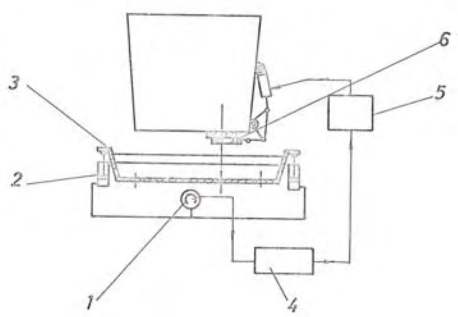


***Fig. 1**. Tenet draft of settlement system of liquid steel level in tundish*

The move and sustenance vertically of machine tundish of continuous casting does by the agency of to a hydraulic indited installations from a behaved electric pump and four hydraulic drums with lifter rods and pistons, dispositioned on the sustenance support of tundish tundish-car. Assigned uniform task on the sustenance pistons of tundish creates in the hydraulic drums a pressure which can be metered.[1]

The level variation in the machines tundish of continuous casting translates in the pressure variation from the hydraulic drums of tundish sustenance, which it transmits to transducers in unified system or pressure-gauges with electric contacts.

The reaction signal, given by transducers is transmitted by impulses to the command element, which it is a tripozitional controller with sampling. Delicate purveyed command by the controller applies hydraulic execution element, which it acts the rectifying mechanism of passage reach.

The running tenet of automatic settlement system of level in tundish is ilustrated of given diagram in figure 2, in which it enters the indicial reply of h(t) system, to an applied variation of reference, the execution size action $x_m$ (the settlement organ opening), and also the delicate purveyed commands controller.

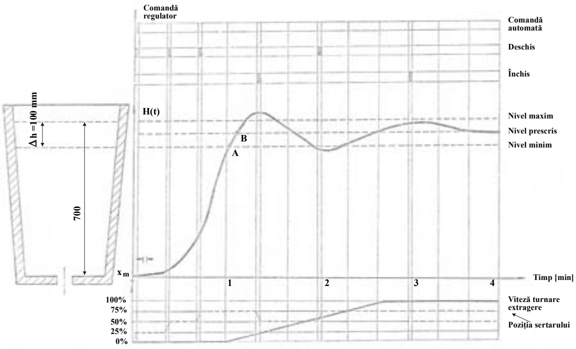


***Fig. 2**. The running tenet of automatic settlement system of liquid steel level in tundish*

## 3. Automatic dynamics installation study

For the controller parameters fitting, for procurance to some imposed performances of automatic settlement system whole, it is needed automatic dynamic installation knowledge, which it includes the spatial mechanism acting. This is imposes mathematical modelling of tuned installation, in stabilization behaviour of liquid steel level.

The representation by input-output sizes of formed installation is given in figure 3, in which: h is the level (the output size), $x_m$ – case opening (execution size), $x_{p1}$ – liquid steel level in the casting container, $x_{p2}$ şi $x_{p3}$ – settlement organs position to the exhaust from tundish, $x_{p4}$ – metal temperature, $x_{p5}$ – steel quality etc. ($x_{pk}$, k = 1, 2, …, are disturbed sizes).

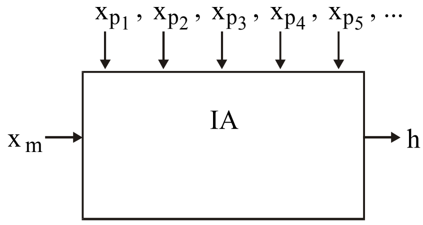


***Fig. 3**. The formed installation representation by input-output sizes.*

The mathematical pattern of automatic installation is formed from state equation, representing the material balance-sheet in tundish and from the relations which explain the intermediate variables which appear in the state equation.

The material balance-sheet equation is:

$$\frac{d(V\rho)}{dt} = Q_1 - Q_2 \tag{1}$$

in which:

V is the liquid steel volume;

ρ – steel consistency

$Q_1$ and $Q_2$ – input debits and, respectively, the output debits.

It does the next hypotheses, according to the physical process:

- The liquid steel temperature variation is negligible, therefore, ρ = constant;
- The interest variation of free surface liquid, in the stabilization behaviour of level, it is negligible.

For a given quality of steel, the disturbed sizes which it intervene are: $x_{p1}$, $x_{p2}$ and $x_{p3}$.

From the relation (1), with the espoused hypotheses, results:

$$A \cdot \rho \frac{dh}{dt} = Q_1 - Q_2 \tag{2}$$

where, A is the free surface area of liquid.

The input debit in tundish is:

$$Q_1 = S(x_m) \cdot \rho \cdot 60 \sqrt{\frac{2gh_1}{2 + \lambda \frac{L}{D}}} \tag{3}$$

in which:

$S(x_m)$ is constructive characteristic of settlement organ to the steel exhaust from the casting container;

$h_1$ – liquid level from the casting container;

D – rated diameter of outflow orifice;

λ - endurance ratio (constant);

L – by-pass span.

The relation (3) it also can put down under form:

$$\begin{aligned} Q_1 &= k_1 \cdot S(x_m) \cdot \sqrt{h_1} = \\ &= k_1 \cdot S(x_m) \cdot \sqrt{x_{p_1}} \end{aligned} \tag{4}$$

where, $k_1$ is a ratio depending the static running point parameters on settlement organ characteristic.

Alike, it infers the debit relation to the exit from tundish:

$$Q_2 = k_2 \cdot \sqrt{h}\left[S_1(x_{p_2}) + S_1(x_{p_3})\right] \tag{5}$$

in which $S_1(x_{p_2})$ and $S_1(x_{p_3})$ are the constructive characteristics of settlement organs to the steel exhaust from tundish, while $k_2$ is a suchlike ratio $k_1$.

The non-linear pattern of automatic installation is:

$$\begin{aligned} A\rho \frac{dh}{dt} &= k_1 S(x_m)\sqrt{x_{p_1}} + \\ &+ k_2 \sqrt{h}\left[S_1(x_{p_2}) + S_1(x_{p_3})\right] \end{aligned} \tag{6}$$

As the installation functions in stabilization behaviour of level, the mathematical pattern can be lineared around rated running point. Considering as all the physical sizes from system hold a constant component (the par) and a variable component, relative small toward the par, namely:

$$\begin{aligned} h &= \bar{h} + \Delta h \\ x_m &= \bar{x}_m + \Delta x_m \\ x_{p_k} &= \bar{x}_{p_k + \Delta x_{p_k}}, k = 1,2,... \end{aligned} \tag{7}$$

where the pars are barred, linearization supposes the relations subrogation (7) in equation (6) and hold the first two terms from the serial development Taylor of non-linear terms

$Q_1 = Q_1(x_m, x_{p_k})$ şi

$Q_2 = Q_2(h, x_{p_2}, x_{p_3})$.

It results as:

$$\begin{aligned} Q_1(x_m, x_{p_1}) &\cong \bar{Q}_1 + \frac{\partial \bar{Q}_1}{\partial x_m} dx_m + \\ &+ \frac{\partial \bar{Q}_1}{\partial x_{p_1}} dx_{p_1} \end{aligned} \tag{8}$$

$$\begin{aligned} Q_2(h, x_{p_2}, x_{p_3}) &\cong \bar{Q}_2 + \frac{\partial \bar{Q}_2}{\partial h} dh + \\ &+ \frac{\partial \bar{Q}_2}{\partial x_{p_2}} dx_{p_2} + \frac{\partial \bar{Q}_2}{\partial x_{p_3}} dx_{p_3} \end{aligned} \tag{9}$$

in which:

$$\bar{Q}_1 = Q_1(\bar{x}_m, \bar{x}_{p_1}),$$

$$\bar{Q}_2 = Q_2(\bar{h}, \bar{x}_{p_2}, \bar{x}_{p_3}),$$

while barred derivatives entails in the rated running behaviour.

Taking account of the expressions (4) and (5), it results:

$$\begin{aligned} Q_1 &= \bar{Q}_1 + \frac{\partial \bar{S}}{\partial x_m} \bar{k}_1 \sqrt{\bar{x}_{p_1} \Delta x_m} + \\ &+ \frac{1}{2} \frac{\bar{k}_1}{\sqrt{\bar{x}_{p_1}}} S(\bar{x}_m) \Delta x_{p_1} \end{aligned} \tag{10}$$

$$\begin{aligned} Q_2 &= \bar{Q}_2 + \frac{1}{2} \frac{\bar{k}_2}{\sqrt{\bar{h}}}\left[S_1(\bar{x}_{p_2}) + S_1(\bar{x}_{p_3})\right]\Delta h + \\ &+ \bar{k}_2 \sqrt{\bar{h}}\left[\frac{\partial \bar{S}_1}{\partial x_{p_2}} \Delta x_{p_2} + \frac{\partial \bar{S}_1}{\partial x_{p_3}} \Delta x_{p_3}\right] \end{aligned} \tag{11}$$

In fixed behaviour, are the valid relations:

$$\bar{Q}_1 = \bar{Q}_2 = \bar{Q} \tag{12}$$

$$\frac{dh}{dt} = \frac{d\Delta h}{dt} \tag{13}$$

$$\bar{k}_1 = \frac{\bar{Q}_1}{S(\bar{x}_m)\sqrt{\bar{x}_{p_1}}} \tag{14}$$

$$\bar{k}_2 = \frac{\bar{Q}_2}{\sqrt{\bar{h}}\left[S_1(\bar{x}_{p_2}) + S_1(\bar{x}_{p_3})\right]} \tag{15}$$

and from the relations (10) and (11) it calculates grafo-analytic, utilizing the constructive characteristics plots of settlement organs.

$$\frac{\partial \bar{S}}{\partial x_m} = \frac{\Delta S}{\Delta x_m}\bigg|_{\bar{x}_m} = S_1 \tag{16}$$

$$\frac{\partial S_1}{\partial x_{p_{2,3}}} = \frac{\Delta S_1}{\Delta x_{p_{2,3}}}\bigg|_{\bar{x}_{p_{2,3}}} = S_{2,3} \tag{17}$$

Replacing the relations (13) and (17) in equations (10) and (11), it results:

$$Q_1 = \bar{Q} + \frac{\bar{Q}}{\bar{S}} s_1 \Delta x_m + \frac{1}{2}\frac{\bar{Q}}{\bar{x}_{p_1}} \Delta x_{p_1} \tag{18}$$

$$Q_2 = \bar{Q} + \frac{1}{2}\frac{\bar{Q}}{\bar{h}}\Delta h + \frac{\bar{Q}}{\bar{S}_{1,2} + \bar{S}_{1,3}}\left(s_2 \Delta x_{p_2} + s_3 \Delta x_{p_3}\right) \tag{19}$$

where are utilized the notations:

$\bar{S} = S(\bar{x}_m)$,

$\bar{S}_{1,2} = S_1(x_{p_2})$ and

$\bar{S}_{1,3} = S_1(x_{p_3})$.

Pursuant to the relations (13), (18) and (19), the state equation of automatic installation becomes:

$$A \cdot \rho \cdot \frac{d\Delta h}{dt} = \frac{\bar{Q}}{\bar{S}} s_1 \Delta x_m + \frac{1}{2}\frac{\bar{Q}}{\bar{x}_{p_1}}\Delta x_{p_1} - \frac{1}{2}\frac{\bar{Q}}{\bar{h}}\Delta h - \frac{\bar{Q}}{\bar{S}_{1,2} + \bar{S}_{1,3}}\left(s_2 \Delta x_{p_2} + s_3 \Delta x_{p_3}\right) \tag{20}$$

It observes as all the ratios from the lineared pattern equation (20) it expresses contingent on the constructive characteristics or the parameters of installation, as well as contingent on the pars of physical sizes ($\bar{Q}, \bar{h}$ etc.), to the numeric values computation of those ratio is a highly simple problem.

Utilizing the notations:

$$T = \frac{2 \cdot A \cdot \rho}{\bar{Q}} \cdot \bar{h} \tag{21}$$

$$k_1 = \frac{2 \cdot \bar{h}}{\bar{S}} \cdot s_1 \tag{22}$$

$$k_2 = \frac{\bar{h}}{\bar{x}_{p_1}} \tag{23}$$

$$k_{3,4} = \frac{2 \cdot s_{2,3}}{\bar{S}_{1,2} + \bar{S}_{1,3}} \cdot \bar{h} \tag{24}$$

the linear pattern of automatic installation becomes:

$$T\frac{d\Delta h}{dt} + \Delta h = k_1 \Delta x_m + k_2 \Delta x_{p_1} - k_3 \Delta x_{p_2} - k_4 \Delta x_{p_3} \tag{25}$$

whereupon it correponds flow-process chart from figure 4.

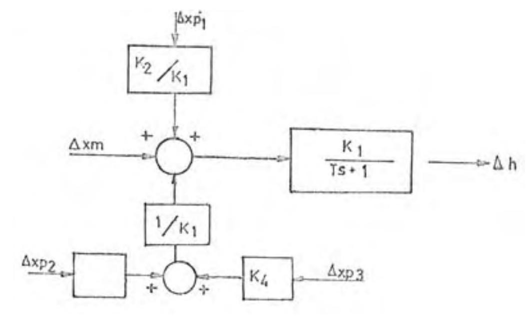


***Fig. 4**. Flow-process chart of lineared pattern of automatic installation*

The lineared pattern ratios computation did in hypothesis as the sizes from system have small variances around pars. This hypothesis is valid for all the sizes from the analysed process, excepting size $x_{p_1} \equiv h_1$. The analytic relation use (23) manages to an incertitude looking the value adoption $\bar{x}_{p1}$. For the exceeding of this problem utilized the curves families which give the debit $Q_1$, contingent on $h_1$ and of equivalent diameter D of outflow reach. In the equation (18), the variable ratio $x_{p1}$ entails average slope of curves which give the debits. In this kind, the relation (18) becomes:

$$Q_1 = \bar{Q} + \frac{\bar{Q}}{\bar{S}} s_1 \Delta x_m + \alpha \Delta x_{p_1} \tag{26}$$

where α it entail chart:

$$\alpha = \frac{\Delta Q_1}{\Delta h_1} \cdot \bar{D} \tag{27}$$

In the final equation, the ratio $k_2$ will entail with the relation:

$$k_2 = \frac{2\alpha\overline{h}}{\overline{Q}} \tag{28}$$

The mathematical pattern of pressure transducer is formally:

$$T_T \frac{dx_r}{dt} + x_r = K_T \Delta h \tag{29}$$

where $T_T$ and $K_T$ are the roll parameters of apparatus.

The mathematical modelling of hydraulic execution element did pursuant to the acquainted methodology establishment of dynamics equations for a tundish system – hydraulic drum. Considering the cynetic energy filling in the elements found in movement and taking account of noted delay [1] with $T_m$, in the command transmission electro-hydraulic, the execution element equation is:

$$T' \frac{d^2\Delta x_m(t)}{dt^2} + \frac{d\Delta x_m(t)}{dt} = \\ = k \cdot x_C(t - T_m) \tag{30}$$

where $x_C$ is given command date of controller.

Flow-process chart of settlement system of level in tundish, with details of mathematical pattern of managed process, is given in figure 5.

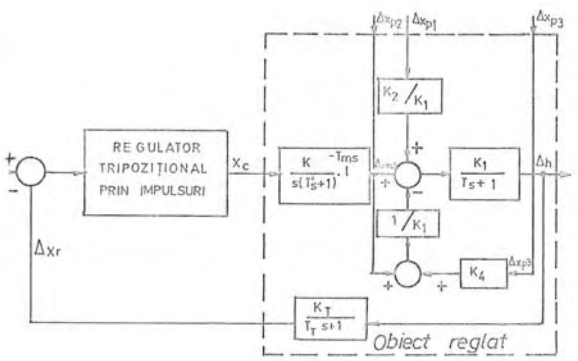


***Fig. 5**. Flow-process chart of settlement system of level in tundish*

## 4. The settlement level system realization in tundish and tests data

The proposed settlement system performances study did by numeric simulation and by experiments on the physical system realized. Analysis on the numeric computer had as the main syock-holders environment number fixing objective of mechanism with case, for dimensions sundries of mould and technological casting parameters. The chased aim is to obtain a number how smaller of stock-holders, for the tax life equals increase, in preservation conditions in imposed limits of level variances. Logical draft of command system on normal function is given infigure 6, while logical draft command of controller by impulses is given in figure 7, in which $PA_{max}$ is the maximum acting pressure, $PA_{min}$ – the minimum acting pressure, DSS – distance between centers, $P_{min}$ and $P_{max}$ – pressure chosen limits.

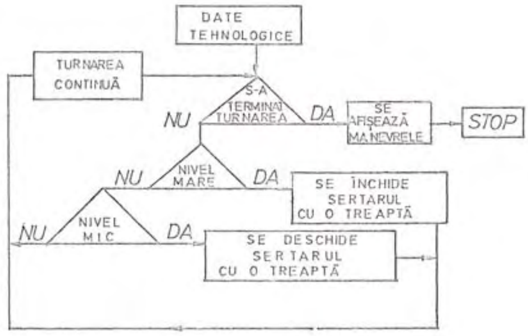


***Fig. 6**. Logical draft of command system on the normal function.*

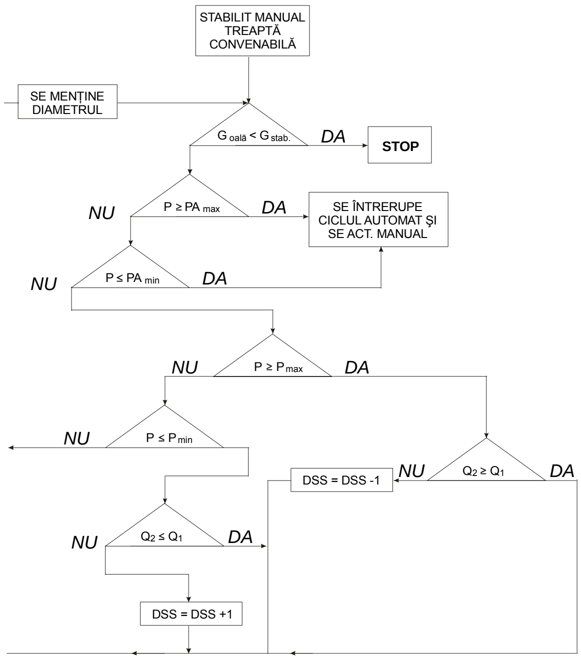


***Fig. 7**. Logical draft of controller by impulses*

In virtue of those logical draft, it realized the programme for the numeric simulation of automatic settlement system function.The obtained outcomes are synthesized in the table 1, looking the stock-holders number of mechanism with case and in the table 2, looking the others technological parameters. It distinguishes the minimal number stock-holders of

[1] The delay period determination $T_m$ was realized by experimental way, analytic evaluations are qualitatively.

spatial mechanism closing with case, which it acknowledges the owned premises in view to the tenet solution establishment.

## 5. Conclusions

The obtained results by continuous casting timing satisfy quite all the quality conditions and technological operation: the level variation stands in admissible limits, the stock-holders number is lowered pursuant analysis on the numeric computer, the level record allows the control as technological document of installation function. In figure 8, are given records of level variation, in manual settlement behaviour and in automatic settlement behaviour, resulting in decisive mode, the performance indices increase to the automatic settlement, by the realized system. During on the all experiments, the automatic settlement appliance adduced a good reliability of operation.

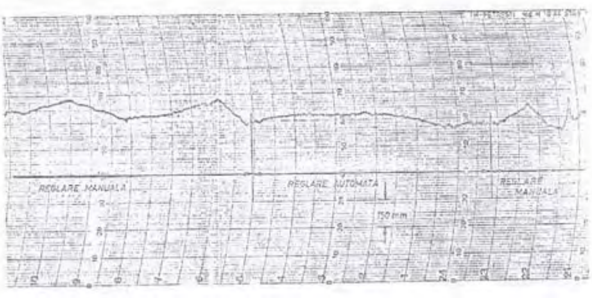

***Fig. 8****. The liquid steel level in tundish in manual and automatic settlement behaviour*

The realization of automatic settlement system of liquid steel level in tundish has importance issues looking the continuous casting slab quality (under the purity aspect in non-metalic inclusions) as well as looking the line punches avoidance, with bearings over indices of output and productivity of continuous casting machines.

***Table 1.*** *Casting time and the stock-holders number of function case of mould tipo-dimension and casting speed*

| | | | | |
|---|---|---|---|---|
| The width of mould (mm) | 1,600 | 1,000 | 1,300 | 1,600 |
| The thickness of mould (mm) | 250 | 200 | 250 | 300 |
| Speed (m/min) | 0.650 | 1 | 0.7 | 0.5 |
| Casting time (min) | 35 | 46 | 39 | 36 |
| The stock-holders number of mechanism with case | 8 | 6 | 4 | 8 |

***Table 2.***

| The thickness (mm) | | 0.150 | | 0.200 | | 0.250 | | 0.300 | |
|---|---|---|---|---|---|---|---|---|---|
| The width (m) | Steel group | Speed [m/min] | Debit Q [t/min] | Speed [m/min] | Debit Q [t/min] | Speed [m/min] | Debit Q [t/min] | Speed [m/min] | Debit Q [t/min] |
| 0.7 | 1 | 1.5 | 1.13 | - | - | - | - | - | - |
| 0.7 | 2 | 1.7 | 1.25 | 1.25 | 1.23 | - | - | - | - |
| 0.7 | 3 | 1.7 | 1.25 | 1.60 | 1.60 | 1.05 | 1.29 | - | - |
| 1 | 1 | 1.5 | 1.58 | 1.00 | 1.40 | 0.70 | 1.23 | - | - |
| 1 | 2 | 1.7 | 1.79 | 1.20 | 1.68 | 0.80 | 1.40 | - | - |
| 1 | 3 | 1.7 | 1.79 | 1.30 | 1.82 | 1.05 | 1.84 | - | - |
| 1.3 | 1 | 1.35 | 1.84 | 1.00 | 1.82 | 0.70 | 1.59 | - | - |
| 1.3 | 2 | 1.35 | 1.84 | 1.00 | 1.82 | 0.80 | 1.82 | - | - |
| 1.3 | 3 | 1.35 | 1.84 | 1.00 | 1.82 | 0.80 | 1.82 | - | - |
| 1.6 | 1 | - | - | 0.8 | 1.79 | 0.65 | 1.82 | 0.50 | 1.68 |
| 1.6 | 2 | - | - | 0.8 | 1.79 | 0.65 | 1.82 | 0.55 | 1.85 |
| 1.6 | 3 | - | - | 0.8 | 1.79 | 0.65 | 1.82 | 0.55 | 1.85 |

## References

[1].**Munteanu V.** – *Instalație de autoreglare a nivelului oțelului lichid în distribuitorul mașinilor de turnare continuă*, Brevet de invenție nr. 78734 - România;

[2].**Orănescu A., Munteanu V., Bocioacă R.** - *Structural Optimizing of the Sliding Gate Nozzle Devices for Casting Ladles*. Buletinul Universității din Galați, 1982, pag. 49-55;

[3].**Munteanu V., Orănescu A.,** – *Posibilități de optimizare a procesului tehnologic de turnare a oțelului.* Simpozion cu tema „Reducerea consumului de materii prime, combustibili și energie" Galați 8-9 aprilie, pag. 237-243.