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COMPARISON OF CALCULATINGS METHODS OF THE MAIN PARAMETERS FOR SINGLE-TIER TUYERES

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Summary. *A large number of articles have been devoted to the problem of calculation of main parameters for single-tier tuyeres. Various methods and equations on the matter have been proposed in the papers. However, they do not provide the necessary information which of these methods allows the obtaining of the main design parameters of single-tier tuyere, which will correspond to the existing standard structures, i.e. will be adapted to modern working conditions of national iron-and-steel enterprises of Ukraine. The creation of above-mentioned methods of calculation is an important question, as it will contribute to the development of more advanced single-tier tuyeres. Five methods have been developed for calculation of the main design parameters of single-tier tuyeres. Appropriate analytical and computational research was conducted using these five methods.*

It was found that the approximate comparison results of the modern main design parameters of single-tier tuyere on the converters of National iron-and-steel enterprises of Ukraine can be obtained by methods one and four. However, the method four requires some additional graphs which can complicate the development of the calculation program for this method.

Key words: *single-tier tuyere, converter, LD-process, main design parameters for the tuyere, calculation method.*

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Problem statement. At present the share of steel obtained in the oxygen steel-making converters in Ukraine is over fifty percent from total amount. LD-process of the converter bath has been the most widely spread one in oxygen-converter plants of national iron-and-steel enterprises of Ukraine [1–18]. The process mostly involves using the single-tier tuyeres aimed at efficient melt blowing and quality metal semi-product obtaining.

We must admit that the problem of calculation of single-tier tuyeres design parameters has been described in a great number of papers among which the most important are [1–15]. Various techniques and relevant equations have been proposed there. Nevertheless, there is no information concerning the choice of methods enabling to obtain main design parameters of the single-tier tuyeres that will correspond to the current standard structures, i.e. they will be adapted to modern working conditions of national iron-and-steel enterprises of Ukraine. The development of such methods is quite an urgent problem as it will facilitate the creation of perfect design of overhead tuyeres. The problem of their introduction is also caused by difficult opeartional conditions being observed nowadays in oxygen-converter plants of national iron-and-steel enterprises of Ukraine.

Analysis of the latest research and publications. The papers [1–15] can be divided into three groups according to the approach dealing with tuyeres parameters calculation. The characteristics of blowing mode are mostly the output data in the approach to the calculation of the first group [6, 13, 14]. Due to this only the parameters concerning the geometrical dimensions of nozzles of a single-tier tuyere tip can be calculated in this case. The papers [4, 5, 12, 15] characterize the approach to the second group. In this case apart from the blowing mode characteristics the design parameters of converter plant and its charge are taken into account both as output data and for the equations of the tuyere parameters. All necessary basic design

Corresponding author: Pavlo Yushkevich; e-mail: isi.dps.r@gmail.com parameters of a conventional tuyere can be determined by these methods. The papers [1–3, 7–11] deal with the approach of the third group. According to these papers the main design parameters are determined using mostly output data that is similar to the approach of the second group. But the papers from the third group expect the use of equations allowing the diameter and depth of interaction reaction zones, core length of oxygen jets and a number of other characteristics to be calculated. It is very important regarding the oxygen jets and the bath surface interaction. Moreover, the equations to determine the initial and operation height of a single-tier tuyere location above the metal melt bath at rest have been proposed in these papers. All this study together with basic design parameters allows having an idea concerning the overhead tuyere operational lifetime and blowing efficiency. Thus, the papers referring to the third group of approaches have enabled us to describe the interconnection between the characteristics of the blowing mode, parameters of converter plants and development of macro physical phenomena which are observed during the blowing. This complex approach may enable to obtain the necessary main design parameters of a single-tier tuyere. Due to this approach the efficient mode of converter bath blowing will be provided preventing a number of errors while in operation.

It should be emphasized that despite the presented separation most of the methods under discussion have enabled to determine the same basic design parameters of single-tier tuyeres. According to the fig. 1: n_l – the number of Laval nozzles, pcs; α – Laval nozzles angle of inclination to the tuyere vertical axis, °; φ – approach angle between axes of neighboring Laval nozzles, °; d_{vh} – enter, d_{kr} – critical and d_{vhd} – exit diameter of Laval nozzle, m; l_d – subcritical (confuser) and l_z – supercritical (diffuser) length of Laval nozzle, m.

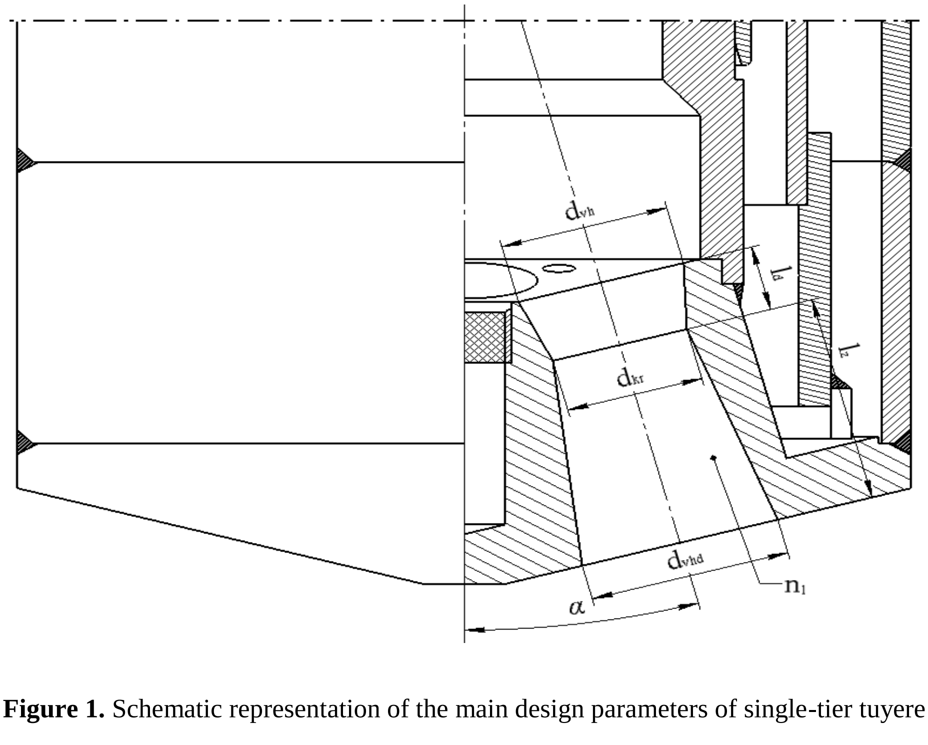

Figure 1. Schematic representation of the main design parameters of single-tier tuyere

Paper purpose. To determine which of the methods under discussion in the paper will enable us to obtain the main design parameters of the single-tier tuyeres that will correspond to the current standard structures, i.e. they will be adapted to modern working conditions of national iron-and-steel enterprises of Ukraine.

Problem setting. To achieve the goal set we should consider and develop some methods based on the papers [1–14]. We will adjust certain calculations of the main design parameters of the single-tier tuyeres to the operational conditions of 160 oxygen converters at PJSC «ArselorMittal Kryvyi Rih», PJSC «AMKR» and 250 at PJSC «Dniprovskyi iron-and-steel works», PJSC «DMK» as they are the leading iron-and-steel enterprises of cyclical turnaround in Dnipro region.

According to [1–14], the obtained results of calculations must be compared with the characteristics of the main design parameters of current standard tuyeres on these enterprises which are given in [16].

Main material. A great number of scientific articles discussing the problem of calculation of single-tier tuyeres has been found and analyzed. It was proved that the most efficient of them regarding to the current operational conditions of national oxygen-converter plants of iron-and-steel enterprises of Ukraine are those which can be determined by the papers [1–14]. Further study of the papers [1–14] has enabled us to formulate five methods of calculation of the main design parameters of the single-tier (conventional) tuyeres. Each of the techniques has specific characteristic features concerning the calculation algorithm and corresponds to the requirements of the goal and problems specified in the paper. Moreover, we should admit that the developed techniques have covered all three groups of approaches to the calculation of the main design parameters of the single-tier tuyeres.

Having compared the above-mentioned five methods developed by the papers [1–14], it was found that they mostly have had the common output data but some of them require the following additional ones: [2] V_u^k – specific volume of the converter, m^3/t; P_{vh} – initial pressure ahead of the Laval nozzles, MPa; T_{vh} – oxygen temperature against the nozzles, K; [4] $Q_{zag}^{O_2}$ – specific intensity of blowing, m^3/t·min; P_{vhd} – Laval nozzle exit pressure, MPa; [5] P_{mag} – gas pressure in workshop pipeline, MPa; $h_{f,\ max}^{rob}$ – maximum working height of a tuyere at blowing, m; [6], [12] m_{O_2} – oxygen mass consumption per time unit, kg/s; D_{tr} – cross section diameter of oxygen supply pipe, m.

Regarding the calculation procedure the methods under consideration have the following specific features. The first developed method according to the papers [1, 3, 7–11] makes possible not only to determine the main design parameters of the single-tier tuyeres but to prove the operational capability of the tuyere of such parameters use in the converter working space. The developed technique consists of 37 equations. It should be admitted, that the above-mentioned calculation technique can provide the designing of shortened Laval nozzles. In this case their geometrical dimensions can be determined by taking into account changes in pressure and gas consumption on entering the nozzle. It allows the Laval nozzle operation in calculation mode under maximum low pressure and gas consumption conditions with little deviation from standard indices. Due to this fact the efficient mode of converter bath blowing has been provided avoiding the tuyere tip erosion caused by the nozzle exit parts removal in contrast to the nozzles which are usually calculated for the exact values of pressure and gas consumption.

According to the second method described in the papers [2, 13, 14] 28 equations are required to make calculations to determine the main design parameters of a single-tier (standard) tuyere. Unlike the previous calculation, it allows, first of all, determine the most efficient number of nozzles under specific technological conditions. Depending on the chosen number of nozzles further determination of other main design parameters of the tuyere is taking place.

The third method is based on the paper [4], where 23 equations are required to calculate the main design parameters of a single-tier tuyere. Unlike the previous methods, it does not allow to find the approach angle between the Laval nozzles axes, to take into account the difference in blowing intensity and pressure in front of the nozzles in the tuyere tip. It must be necessary for the certain production process conditions.

The fourth method has been developed on the basis of paper [5], previously proposed by the Iron and Steel institute. According to the method, the number of nozzles must be determined due to the minimal or maximum blowing consumption specified for the production needs. Other parameters of the tuyere can be found by the chosen number of nozzles from 18 equations and special developed graphs. The calculation performed by [5] is the only one which has been studied in the paper allowing main design parameters of the single-tier (standard) tuyere to be determined due to graphs and equations. In this case the determination of values of main design parameters of the tuyere is based on the interrelation of certain characteristics. By this method the calculation of shortened nozzles of a tuyere is possible. Method [5] does not allow the approach angle between the nozzles axes to be found. Nevertheless, it determines the diameter of circumference where the axes of nozzles exit cross sections are located.

The last, fifth, method [6, 12] allows the calculation to be made only by 15 equations without any additional graphs. Due to this fact most of main design parameters of the single-tier (standard) tuyere can be found as quickly as possible. Unfortunately, the method does not allow the angle of inclination of Laval nozzles to the tuyere vertical axis and the approach angle to be found. Other main design parameters are determined according to the type of calculation of Laval nozzle.

According to the five methods under consideration developed on the basis of the material of papers [1–15], the tables 1–5 have been compiled. The equations to calculate the specified in the paper main design parameters of the single-tier tuyere have been given in the tables. Table 1 represents the equations for calculating the number of Laval nozzles in a single-tier tuyere according to [1–15].

Table 1

Equations for calculating the number of Laval nozzles in a single-tier tuyere

№	Equations	Symbols and units of measurement	References
I	II	III	IV
1	$n_l^{min} = 0{,}35 \cdot \frac{(Q_{zag}^{O_2})^{1{,}17} \cdot H_0^2}{(V_u^k)^{1{,}7}}$	n_l – number of Laval nozzles, pcs.	[2], [12]
2	$n_l^{max} = 1{,}5 \cdot \frac{(Q_{zag}^{O_2})^{1{,}17} \cdot G_n}{H_0^{0{,}33} \cdot 100}$	H_0 – converter bath depth at rest, m.	[2], [12]
3	$n_l = (G_n \cdot Q_{zag}^{O_2})/e^{\frac{\ln H_u + 0{,}163}{0{,}428}}$	G_n – converter nominal volume, t.	[3]
4	$n_l = \frac{q_{osn}^{O_2}}{\left(H_u/0{,}85\right)^{2{,}34}}$	H_u – height of converter notional free volume, m; $q_{osn}^{O_2}$ – oxygen consumption per group of Laval nozzles, m^3/min.	[1], [7]
5	$n_l = \frac{q_{zag}^{O_2}}{q_1^{O_2}}$	$q_{zag}^{O_2}$ – blowing total intensity, m^3/min; $q_1^{O_2}$ – intensity per nozzle, m^3/min.	[2], [12], [13]
6	$n_l = (G_n \cdot Q_{zag}^{O_2})/e^{\frac{\ln H_u + 0{,}163}{0{,}428}}$	G_n – nominal volume (capacity) of converter, t.	[3]
7	$n_l = \frac{q_{zag}^{O_2}}{(q_1^{O_2})^{dop}}$	$(q_1^{O_2})^{dop}$ – allowable oxygen consumption per Laval nozzle, m^3/min.	[4]
8	$(n_l)_r = \frac{q_{zag}^{O_2}}{q_r^{O_2}}$	$q_r^{O_2}$ – theoretical oxygen consumption through the Laval nozzle, m^3/min.	[5]

(to be continued)

I	II	III	IV
9	$n_l = \frac{(q_{zag}^{O_2} - q_{dod}^{O_2})}{(H_u/0{,}85)^{2,34}}$	$q_{dod}^{O_2}$ – blowing intensity on additional group of nozzles, m^3/min.	[9]
10	$n^{max}{}_l = \frac{k_{18} \cdot (Q_{zag}^{O_2} \cdot G_n)}{H_0^{1\text{-}u}}$	k_{18} =150·10^{-4} – proportionality coefficient; u = 0,67 – degree index.	[14]
11	$n^{max}{}_l = k_{16} \cdot \frac{Q_{zag}^{O_2} \cdot G_n}{\left(V_u^k\right)^z \cdot H_0^{1\text{-}u}}$	k_{16} = 9,0·10^{-3} – proportionality coefficient, from the experimental data.	[14]
12	$n_l = 0{,}23 \cdot \frac{(Q_{zag}^{O_2})^{1,17} \cdot H_0^{2,5}}{(V_u^k)^{1,7}}$	V_u^k – specific volume of converter, m^3/t; $Q_{zag}^{O_2}$ – specific intensity of blowing, m^3/t·min.	[15]

The efficiency of single-tier tuyeres use [1–15] is also greatly influenced by the angle of inclination of Laval nozzles α to the conditional vertical axis of blowing plant. The angle of inclination of Laval nozzles to the vertical axis of the single-tier tuyere can be determined by different equations as well. These equations are given according to the table 2 compiled by the papers [114].

Table 2

Equations for calculating angle of inclination of Laval nozzles to the vertical axis of the single-tier tuyere

№	Equations	Symbols and units of measurement	References
I	II	III	IV
1	$\alpha = arcsin\ (\ sin\varphi / 2\ )/(\ sin180 / n_l\ )$	α – angle of inclination of nozzles, °. φ – approach angle between the nozzles axes, °.	[1], [3], [7], [9]
2	$\alpha \ \geq arctg\ \frac{D_{r\ z}}{4 \cdot (h_f + L_{r\ z}) \cdot sin180/n_l}$	$L_{r\ z}$ – depth of oxygen jet penetration into metal, m; h_f – height of a tuyere location at blowing, m.	[2]
3	$\alpha \geq 3 \cdot n_l$	n_l – number of nozzles in a tip, pcs.	[4]
4	$\alpha = arctg \frac{D_{r z}}{4 \cdot sin\varphi / 2 \cdot \left(h + L_{r z}\right)}$	$D_{r z}$ – reaction zone diameter, m; h – height of a tuyere at blowing, m.	[13]

It must be emphasized, that the blowing mode is greatly influenced by the angle α value. Moreover, α influences the configuration and pattern of reaction zones formation while oxygen jets are interacting with the melt surface in the converter bath. At its low value the reaction zones can run into single combined zone of interaction. In case of its high value they are divided into separate zones and form some local sites of jets interaction with the melt surface in the oxygen converter bath. Apart from angle α the pattern of reaction zones of interaction formation, their configuration is greatly influenced by the approach angle φ. To determine the approach angle φ between the adjacent nozzles axes in the blowing unit the equations given in the table 3 have been proposed.

Table 3

Equations for calculating the approach angle between the adjacent nozzles axes in the blowing unit of the single-tier tuyere

№	Equations	Symbols and units of measurement	References
I	II	III	IV
1	$\varphi = 2 \cdot arctg \dfrac{D_{r\,z}^{I\ max} - d_v}{2 \cdot (h_f^{rob} + l)}$	d_v – minimal distance between the nozzles axes of internal contour, m; h_{rob}^{f} – tuyere working height, m; $D_{r\,z}^{I\ max}$ – maximum diameter of initial zone, m.	[1], [7]
2	$\varphi = 2 \cdot arcsin\left(sin\,\alpha \cdot sin \dfrac{180}{n_l} \right)$	φ – approach angle between the nozzles axes, °; α – angle of inclination of nozzles in a tip,°; n_l – number of nozzles in a tuyere tip, pcs.	[2], [12]
3	$\varphi = 2 \cdot arctg \dfrac{D_{r\,z}^{I}}{2 \cdot (h_f + L_{r\,z}^{I})}$	$D_{r\,z}^{I}$ – diameter of initial zone, m; $L_{r\,z}^{I}$ – depth of initial zone of interaction, m.	[12]
4	$\varphi = 2 \cdot arctg \dfrac{D_{max}}{2 \cdot (l_{st}^{poch} + 0{,}5 \cdot L_{min})}$	l_{st}^{poch} – length of initial speed core, m; $D_{\max}$ – maximum diameter of jet part of reaction zone, m; $L_{\min}$ – minimal length of jet part of reaction zone, m.	[3]
5	$\varphi = 2 \cdot arctg \dfrac{D_{r\,z}^{I\ min} - d_v}{2 \cdot (h_f^{rob} + l)}$	$D_{r\,z}^{I\ min}$ – diameter of initial reaction zone, m; l – length of jet of initial reaction zone, where the last one approaches the maximum diameter, m.	[9]

The basic geometrical design parameters of Laval nozzles at the tip of single-tier tuyere have been proposed to determine from the equations give in in the tables 4 and 5. Laval nozzles must provide the continuous flow of gas jets and steady run of blowing. We should also take into consideration the balance of basic geometrical indices of nozzles d_{vh}, d_{vhd}, d_{kr}, l_z, l_d as it must guarantee the efficient throughput capacity to supply cooling water in the single-tier (standard) tuyere tip. It is greatly influenced by the nozzles size and their number. It should be emphasized that the length of subcritical l_z (diffusor) and supercritical parts of Laval nozzle l_d (confusor) depend on the diameters d_{vhd}, d_{kr}, which are the basic parameters in most equations for their calculations according to table 5.

Table 4

Equations for calculating the diameters of the main cross sections of the Laval nozzle at the tip of single-tier tuyere

№	Equations	Symbols and units of measurement	References
I	II	III	IV
1	$d_{kr} = d_{vh} \cdot \sqrt[3]{\left(1 - \dfrac{\rho_{kr} \cdot w_{kr}^2}{\rho_{vh} \cdot w_{vh}^2}\right)^2}$; $d_{vh} = 1{,}26 \cdot d_{kr}$; $d_{vhd} = a \cdot l_{st}^{poch} / 0{,}34$	ρ_{kr} – oxygen density in critical cross section, kg/m^3; w_{kr} – velocity in critical cross section, m/s; l_{st}^{poch} – core length of initial velocity, m; a – coefficient of jet turbulent structure, a = 0,08.	[2]

(to be continued)

I	II	III	IV
2	$d_{kr} = 2\sqrt{f_{kr}/\pi}$; $d_{vhd} = 2\sqrt{f_{vhd}/\pi}$; $d_{vh} = d_{kr} + 2 \cdot r_d \cdot \cos \beta/2 -$ $- r_d \sqrt{3 + 4 \cdot \sin \beta/2 - 4 \cdot \sin^2 \beta/2}$	f_{kr} – area of nozzle critical cross section, m^2; f_{vhd} – area of nozzle exit cross section, m^2; β – expansion angle of the supercritical part of nozzle, °.	[3],[11], [15]
3	$d_{vhd} = (4 \cdot f_{vhd}/\pi)^{0,5}$; $d_{vh} = (4 \cdot m_{O_2}/\pi \cdot \rho_{vh} \cdot w_f)^{0,5}$	m_{O_2} – oxygen mass consumption per unit of time, kg/s; w_f – velocity in the tuyere pipe $50...100$ m/s.	[4]
4	$d_{vhd} = \sqrt{\varepsilon} \cdot d_{kr}$;	ε – nozzle expansion degree; d_{kr} – diameter of nozzle critical cross section, m.	[6]
5	$d_{kr} = 11{,}18\sqrt{\dfrac{q_1^{O_2}}{P_{vh}^{pov}}}$; $d_{vh} = (1{,}1 \div 1{,}3) \cdot d_{kr}$	$q_1^{O_2}$ – blowing intensity per nozzle m^3/min; P_{vh}^{pov} – full initial pressure, MPa; d_{vh} – diameter of Laval nozzle entry (inlet), m.	[5]

Table 5

Equations for calculating the length of the subcritical and supercritical parts of the Laval nozzle at the tip of single-tier tuyere

№	Equations	Symbols and units of measurement	References
I	II	III	IV
1	$l_z = (d_{vhd} - d_{kr})/2 \cdot tg\ \beta/2$; $l_d = 0{,}5 \cdot d_{kr}$	l_d – length of the subcritical part of nozzle, m; l_z – length of the supercritical part of nozzle, m; d_{vhd} – diameter of the nozzle exit cross section, m.	[2–5], [11], [15]
2	$l_d = \dfrac{(d_{vh} - d_{kr})}{2 \cdot tg \dfrac{\beta_d}{2}}$	d_{vh} – diameter of nozzle entry (inlet), m; β_d – expansion angle of the subcritical part of nozzle β_d from 20 to 30°.	[4]
3	$l_d = (0{,}5 \div 1{,}0) \cdot d_{kr}$	d_{kr} – diameter of the nozzle critical cross section, m;	[5]
4	$l_z = \dfrac{\sqrt{f_x} - \sqrt{f_{kr}}}{\sqrt{\pi} \cdot tg \dfrac{\beta}{2}}$	r_{kr} – Laval nozzle radius in critical cross section; β – expansion angle of the supercritical part of nozzle °.	[6]

Due to the great number of equations according to [1–14] given in tables (1–5) which can be used for the calculation of the same main design parameters of the single-tier (standard) tuyere one should find out which of them are necessary for the tuyere standard design calculations. It means which of them are adapted to the current operational conditions of oxygen-converter plants of national iron-and-steel enterprises of Ukraine.

For that purpose the calculations for the operating condition of oxygen converters of PJSC «ArselorMittal Kryvyi Rih», PJSC «AMKR» and PJSC «Dniprovskyi iron-and-steel works», PJSC «DMK» have been made by five selected and formed methods using the equations from the tables 1–5. We must admit that PJSC «AMKR» and PJSC «DMK» are the leading iron-and-steel enterprises of cyclical turnaround in Dnipro region.

Analysis of calculations results. According to the results of calculations made for the operating condition of 160 converters at PJSC «ArselorMittal Kryvyi Rih» and 250 at PJSC «Dniprovskyi iron-and-steel works» five options of main design parameters of the single-tier (standard) tuyeres have been obtained for each enterprise. Five methods have been used on the basis of papers [1–14] keeping to the same output data in each type of calculation. They have been compared with parameters of conventional standard design of the tuyere of PJSC «AMKR» and of PJSC «DMK» and the results are given in tables 6 and 7.

Table 6

Comparison of calculation results by the developed methods according to works [1–14], with parameters of a standard design of single-tier tuyere for 160 t converters of PJSC «AMKR»

Basic design parameters for a single-tier tuyere designing	symbols	Calculation results by the developed methods					PJSC «AMKR»
		[1, 3, 7–11]	[2, 13, 14]	[4]	[5]	[6], [12]	standard design according to [16]
I	II	III	IV	V	VI	VII	VIII
Number of Laval nozzles, pcs	n_l	4	4	5	5	6	5
Angle of inclination of Laval nozzles, °	α	15	14	15	14	-	20
Approach angle of Laval nozzles, °	φ	20	20	-	-	-	-
Entry (inlet) diameter of a nozzle, m	d_{vh}	0,04	0,041	0,043	0,037	0,042	0,036
Exit diameter of a nozzle, m	d_{vhd}	0,042	0,041	0,046	0,041	0,044	0,039
Critical diameter of a nozzle, m	d_{kr}	0,035	0,033	0,03	0,032	0,035	0,032
Subcritical length of a nozzle, m	l_d	0,018	0,017	0,03	0,024	0,018	0,015
Supercritical length of a nozzle, m	l_z	0,067	0,044	0,092	0,06	0,049	0,064

Table 7

Comparison of calculation results by the developed methods according to works [1–14], with parameters of a standard design of single-tier tuyere for 250 t converters of PJSC «DMK»

Basic design parameters for a single-tier tuyere designing	symbols	Calculation results by the developed methods					PJSC «DMK»
		[1, 3, 7–11]	[2, 13, 14]	[4]	[5]	[6], [12]	standard design according to [16]
I	II	III	IV	V	VI	VII	VIII
Number of Laval nozzles, pc	n_l	5	6	10	5	9	5
Angle of inclination of Laval nozzles, °	α	20	19	30	18	-	17
Approach angle of Laval nozzles, °	φ	23	18	-	-	-	-
Entry (inlet) diameter of a nozzle, m	d_{vh}	0,048	0,45	0,4	0,047	0,42	0,046
Exit diameter of a nozzle, m	d_{vhd}	0,057	0,046	0,048	0,062	0,43	0,060
Critical diameter of a nozzle, m	d_{kr}	0,041	0,036	0,028	0,042	0,34	0,041
Subcritical length of a nozzle, m	l_d	0,0205	0,018	0,018	0,031	0,022	0,014
Supercritical length of a nozzle, m	l_z	0,069	0,057	0,046	0,121	0,052	0,0715

Tables 6–7 prove that most of calculations made on the basis of material in the papers [1–14] allow the approximate values of the main design parameters to be obtained in case of standard single-tier tuyere. First of all, it is made for the tuyere design in 160 converters at PJSC «AMKR». In case of 250 converters at PJSC «DMK», the most suitable results have been obtained by method one [1, 3, 7–11] and four [5].

Moreover, we should admit that according to all calculations made and given in tables 6–7 for the operating conditions of PJSC «AMKR» and PJSC «DMK» the obtained values of angle of inclination of Laval nozzles to the vertical axis of the single-tier tuyere α do not correspond to the standard design parameters. In case of PJSC «AMKR» calculation values α range from 14 to 15°, but for the standard design is 20°. For the operating conditions of PJSC «DMK» calculation values range from 18 to 30° unlike the standard tuyere where it equals to 17°. We can assume that these are the values of Laval nozzles angles of inclination α of standard design. They have been chosen due to certain technological and design consideration by the developers of these options of the tuyere design for PJSC «AMKR» and PJSC «DMK».

From five developed methods on the basis of papers [1–14] the most approximate results by most calculated main design parameters for the operating conditions of PJSC «AMKR» and PJSC «DMK» have been obtained by the first [1, 3, 7–11] and fourth [5] methods.

Nevertheless, in case of method 4 [5], whilst calculating the operating conditions for PJSC «DMK» a considerable deviation of values in Laval nozzles length is being observed. It can be explained by the fact that the nozzles on the current design PJSC «DMK» are purposely made as shortened ones [16] to be adapted to pressure range from P_{min} to P_{max} and gas consumption from $q_{\min}$ to $q_{\max}$ at the entry to subcritical section of Laval nozzle so that to provide the efficient mode of blowing of the converter bath and avoid the tuyer tip erosion under unstable operating conditions of oxygen-converter plant. This is very important for the current operating conditions of national iron-and-steel enterprises of Ukraine. We must emphasize that while making calculations for PJSC «AMKR» and PJSC «DMK» whose results are given in tables 6–7 according to method 4 [5] we did not take into consideration the possibility of the tuyere with shortened Laval nozzles development. Though their calculation is possible if necessary similar to the method developed according to [1, 3, 7–11].

The calculations made by the method 1 developed on the basis [1, 3, 7–11] had to determine the main design parameters of a standard single-tier tuyere by the algorithm of 37 equations. In case of method 4 [5], the calculations were made by the algorithm of 18 equations. Thus, method 4 has cut down the time consumption considerably and enabled quite approximate results to be obtained by [5] for the standard design of single-tier tuyeres both on PJSC «AMKR» and PJSC «DMK». Nevertheless, the thing is that unlike the method 1 [1, 3, 7–11], it is impossible to determine the approach angle between the neighboring axes of the tuyere nozzles by method 4 [5]. In case of [5] a number of important parameters can be obtained only by graphs construction. Without relevant graphs any further calculations are impossible and this makes some difficulties in the calculation program development.

Conclusions. Thus, we have come into conclusion that nowadays there is no idea what kind of method is the most efficient one to determine the main design parameters of the conventional single-tier (standard) tuyeres, i.e. the tuyeres which will meet the requirements of the current standard design adapted to modern conditions of national iron-and-steel enterprises of Ukraine.

Necessary analytical study has been conducted on the number of papers concerning the matter under discussion. Five methods aimed at determination of the main design parameters of the single-tier tuyeres have been developed. These methods have specific characteristic features in calculations algorithm and meet the requirements of the set purpose and problems. We should also emphasize that these methods cover all three groups of approaches to the calculation of the main design parameters of the single-tier tuyeres.

The appropriate analytical-calculation study has been conducted on the basis of the developed five methods. As a result, five options of the main design parameters of the single-tier tuyeres for the operating condition of 160 converters at PJSC «ArselorMittal Kryvyi Rih» and 250 at PJSC «Dniprovskyi iron-and-steel works» have been obtained. The calculation results have been compared with the parameters of standard design of conventional single-tier tuyeres. It has made possible to find out that the most suitable results to the current operating conditions of national iron-and-steel enterprises of Ukraine can be obtained due to the methods 1 and 4. Method 1 expects the calculation algorithm consisting of 37 equations to be used and allows the main design parameters of the single-tier tuyeres to be obtained. Moreover, it enables to calculate the shortened Laval nozzles. Unlike previous method, method 4 makes calculations using 18 equations. In this case time consumption is less though we need to construct some additional graphs. Besides, method 4 does not allow the approach angle between the tuyere nozzles axes to be calculated. Thus, the necessity of some extra graphs construction by method 4 may complicate the development of appropriate calculation program.

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СПІВСТАВЛЕННЯ МЕТОДИК РОЗРАХУНКУ ОСНОВНИХ КОНСТРУКТИВНИХ ПАРАМЕТРІВ ОДНОЯРУСНИХ ФУРМ

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Резюме. *Питанню розрахунку конструктивних параметрів одноярусних фурм присвячена велика кількість робіт, в яких запропоновано різноманітні методики та рівняння для цього. Однак відсутня інформація щодо того, які з цих методик дозволяють отримати основні конструктивні параметри одноярусних фурм, що будуть відповідати діючим штатним конструкціям, адаптованим до сучасних умов роботи Національних металургійних підприємств України. Наявність свідчень стосовно таких методик необхідна, так як буде сприяти розробленню досконаліших конструкцій верхніх фурм. Потреба впровадження в них постала у зв'язку зі складними умовами роботи, що спостерігаються на сьогодні у киснево-конвертерних цехах Національних металургійних підприємств України.*

Проведено аналітичні дослідження за рядом робіт з цього питання. Сформовано п'ять методик для визначення основних конструктивних параметрів одноярусних фурм. Кожна з методик має певні характерні відмінні риси в алгоритмі розрахунків та відповідає вимогам поставленої мети й завдань у роботі. Треба також відзначити, що сформовані методики охоплюють усі три групи підходів до розрахунку основних конструктивних параметрів одноярусних фурм.

За цими п'ятьма методиками проведено відповідні аналітично-розрахункові дослідження. У результаті отримано п'ять варіацій основних конструктивних параметрів одноярусних фурм для умов роботи 160-ти конвертерів ПАТ «АМКР» та 250-т ПАТ «ДМК». Співставлення їх з параметрами штатних конструкцій діючих одноярусних фурм дозволило встановити, що найбільш відповідні результати до сучасних умов роботи Національних металургійних підприємств України можливо отримати за методикою один та чотири.

Методика один передбачає алгоритм розрахунку за 37 рівняннями. Вона дозволяє отримати усі основні конструктивні параметри для одноярусної фурми з можливістю розрахунку укорочених сопел Лаваля. Методика чотири на відміну від попередньої надає можливість провести розрахунок за 18 рівняннями. Це суттєво скорочує витрату часу, але для методики чотири необхідне проведення ряду додаткових графічних побудов. За методикою чотири неможливо встановити кут у плані між осями сопел фурми. Необхідність проведення додаткових графічних побудов за четвертою методикою може ускладнити розроблення розрахункової програми.

Ключові слова: *одноярусна фурма, конвертер, верхня продувка, основні конструктивні параметри фурми, методика розрахунку.*

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