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Effect of Heat Loss on the Working Index of Electric Arc Furnace (EAF)

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Abstract
Day in day out of human life the use of metal is inevitable, metals are needed for different purposes such as in construction of bridges houses, roads etc. But despite the availability of huge amount of metal, it does not meet the global demand thus this paper investigate the effect of reduction of power of heat loss on the cost of production of electric arc furnace. In order to achieve maximum precision during production, getting product at relatively reduced price has remained a major challenge to the scientists. The experiment was conducted at industrial scale whereby power of heat loss was varied from 7.707-4.624 MW while energy consumption fell from 0.5463 to 0.5317 MW-Hour per ton and productivity tremendously increased from 253.0 ton to 254.0 ton per hour. Data used were collected from active furnace in Zerepaves Metallurgical plant, Russia and further analyzed with software package for accuracy.

Keywords: *Furnace Heat loss; metallurgical plant; cost price*

1. Introduction

Electric steelmaking in an electric arc furnace (EAF) is the main process route for steel scrap recycling and the second most important steel production route in the world. As an energy intensive process, the EAF is responsible for approximately 3% of the total industrial electricity consumption and a significant lever for energy efficiency optimization (International Energy Agency, 2014). As off-gas flow represents an energy output of 20 to 30% of the total EAF energy input, the off-gas is in the focus of current developments to increase the energy and resource efficiency of the EAF, As one of the main continuously measureable process values, the off-gas composition can be utilized to improve the process control and allows conclusions to be made concerning the process behavior > Here process models have proven their applicability for process control and their capability to contribute towards a more detailed understanding of heat and mass transfer during the melting process. In times of continuously growing computational capacity, the complexity of the dynamic process simulation models has increased due to consideration of more and more phenomena (Logar et al. 2012a, b and c) presented a comprehensive deterministic EAF model, which is based fundamental physical and mathematical equations. The model includes all main thermal, chemical land mass transfer phenomena in the EAF. These are implemented via first order ordinary differential equation (ODEs). It was further developed and enhanced with a more detailed simulation of the arc heat distribution and modified chemical module (Saboohi et al., 2017; Fathi et al., 2015).

Electric arc furnace losses heat through lining in form of convectional heat giving-off from part of the surface corpus and $F_{k.t.o}$ in water cooling elements FB radiating through open working and open working plane window During the time of mechanized bottom refueling loading and (dumping of scrap) F1, that convection through graphitized electrode F70 on changing enthalpy of gases, passing through working plane Ft In energy balance, compounded for definition of power of EAF, consider possible enthalpy change of material HF, which in the case observed heat supply effectively (At lower temperature of living compounded also heat loss of working plane of EAF, By measuring the heat of living or when loading scrap (Budding material) when effective heat convection rises from living HF decreases to zero and even symbol changes formed some heat supply on the working plane (Egorov, 1990).

In steel making industry, EAF are considered as one of the systems with the largest consumption of electrical energy. Modern EAFs, besides other forms of energy, such as gas burners and oxygen additions, in average consume from 400 to 500 kWh of electrical energy per ton of steel (Barker et al., 1998). In order to reach such as consumptions, several new technologies were introduced in the past decades, off-gas and slag heat recovery (Lee and Sohn, 2014; Gandt et al., 2016; Barati et al., 2011), CO post-combustion, oxy-fuel burners (Kirschen et al., 2008), oxygen addition (Lee et al., 2014), high power transformer (Bisio et al., 2000), bottom stirring, and many others Furthermore, several approaches to enhance or optimize the EAF control or its subsidiary systems have been proposed (Bekker et al. 2000; Oosthuizen et al., 2004; MacRosy and Swartz, 2005; Saboohi et al., 2019; Leon et al., 2020), with the goal of lowering the production costs of the EAF, In this regard, electrical energy consumption (EEC) has also been a subject of considerate attention. Several studies on prediction of the EAFs EEC using different modeling approaches have been performed (Chen et al., 2018; Kovacic et al., 2019; Carlsson et al., 2019) based either on commercial software, regression methods or different artificial-intelligence approaches. The methods in such studies usually focus on calculating a reliable

EEC forecast and not as much on the factors that cause the fluctuations in EEC, or on the ideas and solutions that would lead to lower EEC. When analyzing an EAF from the energy point of view, two groups of factors that influence the EEC, can be formed, i.e, technology related, and operation related. Technology-related factors are known and comprise different auxiliary EAF systems mentioned in the previous paragraph, which lower the overall EEC. Their influence on EAFs energy balance was analyzed and presented in many publications and is validated in the industrial environments. On the other hand, the influence of operation-related factors, such as the charged scrap types and weight, additions and operational delays, to EAFs EEC is not examined as thoroughly and not as evident as the first category. Only a few studies exist, trying to explain the above factors to the EAF EEC, which are reviewed hereinafter

EAF EEC, $F_{K.T.o}$=Heat loss defined by Newton s formula, $\alpha\varepsilon$= coefficient of heat giving, consider in general form convective and heat exchange of surface (plane), $T_{T>O}$=working temperature, T_B=temperature of surrounding, $q\varepsilon$=Density of heat supply , ΔT=Change in temperature, $S_{T.O}$=Area of heat giving surface, NU=Nusseta number, Nu= C(Gr, Pr), C=coefficient of exponential index depend on instance regime, Gr=Grascove Number, Pr= Prandilite number, P_{HL}=Heat loss, h=Depth of basin.

2. Method

For the active EAF by experimental measurement of energetic balance when temperature of heat giving plane is known as $T_{T,C}$ Heat loss $F_{K.T.O}$ defined by newton formula:

$$F_{K.T.O}=\alpha\varepsilon_x S_{T.O}(T_{T.O} - T_B) = q\varepsilon\, S_T. \quad (1)$$

Where, $\alpha\varepsilon$= coefficient of heat giving, considered in general form convection and heat exchange of surface (plane) with the surrounding with temperature TB.

$$q\varepsilon=\alpha\varepsilon_x(T_{T.O}-T_B)=q\varepsilon_x\Delta T\text{-density of heat supply} \quad (2)$$

Where, ΔT=temperature change; $S_{T.O}$= from 1m^2 area of heat giving surface.

Coefficient of convective heat supply can be defined from the (criteria) Nusseta Number Nu=ȧkⱣo/λ on the base of generalized dependence of M.A Miheeva for different possible regimes free flow fluid (air) in an unlimited plane:

$$Nu=C(Gr\ Pr)^n \quad (3)$$

Where $Gr = g x \beta x \Delta T x e^3/Ƴ^2$ -Graskov number; $Ᵽr = Ƴ/a$ – prandilite number; g= acceleration due to gravity, equal to $9.81ms^{-2}$; λ , Ƴ, β, a = corresponding coefficient of heat convection, kinematic viscosity, volumetric expansion and temperature – convection of fluid (air), depending on temperature; $Ᵽ_O$ = can be defined from linear measurement (linear scale).

Heat loss through working window of EAF which is noted to be (10-15%) general heat loss as a result of significant dimension of window and water cooling element (frame, arc, e.t.c.).
Heat loss radiating through open working window for the time T_0 (Hour) calculated by Stephen

$$W_0 = \mathcal{E}_{1}\text{-}b\delta_0(T_1^4 T_B^4)S_0.T_{0.}.10^{-6} \quad (4)$$

Where S_0=area of open window; $\mathcal{E}_1\text{-}b = \varepsilon_\Psi$- The degree of blacking of working space of EAF when emission through working window, having heat-insulation in its surrounding with temperature T_B;

$\mathcal{E}$ = degree of blackness; equal to 1 for small outlet, emitting like the absolute black body, and 0.6-0.8 for big outlet; Ψ = coefficient of diaphragm depending on the relation of dimension of the outlet. During water coolinof the working window coefficient of diaphragm Ψ in the formula is equal to 1. S_o far the temperature of the air T is significantly lower than temperature.

$$T_1, T_0, T1^4 >> T_B^4 \quad (5)$$

Therefore, for the condition of heat exchange emission through opened working window EAF formula can be simplified, mW-Hour:

$$W_o \text{ equal to } 4.5 \text{ x } 10^{-14} \text{ x } T_1 \text{ X } S_0 \text{ X } T_0. \quad (6)$$

For reduction of heat through working window of the average and mighty furnaces in the inner part construction additional outlet, dimensional of 200x250 mm, with closable door for conducting technological operations on taking probe of metal and slag, temperature measurement of the basin e.t.c, which allows reducing S_0 x T_0.

Heat loss through gases connected to their enthalpy change depend on quantity and content on technological gases formed on the quantity of assimilated into the working plane of EAF gases and on the average temperature of outgoing gases during the smelting period. Intensity of gas liberation from EAF depends on many technological factors, which changes during smelting within the range 50-500 mm^3 (ton.Hour) by temperature 1700-1800 k. Gaseous phase of EAF formed from assimilated air blown oxygen (during the melting period) and oxygen from oxides of different elements, carbon of the budding, graphite electrode and non-carbonized additives, and hydrogen (during dissociation of steam), consists of oxides (40-50%) and dioxides (25-30%) of carbon, Nitrogen (25-30%). Oxygen (up to 10% in the oxidizing period) and hydrogen (up to 1%).

Availability of oxides of carbon in furnace makes them burning and explosively dangerous; volumetric heat of burning is 3.5-5 MJ/m^3. Also gases by 1500-1900K escape in physical heat loss up to 2.5 MJ/m^3.

3. Results and discussion

For evaluation of possibilities of varying the power of heat loss attached to the basic variant, we need to know the dimension of the bathe and working plane of the furnace. We need those things for calculation of height , thickness of slag depends on its mass . But value of height of slag allows evaluation of percentage of length of electric arc Lg of open slag. Parameter of electric arc necessary for calculation of Lg can be founded from the table of electrical characteristics of basic variant of smelting (Table 1).

Definition of the working plane and lining of the furnace dimensions are defined for the furnace of given capacity (G), that contain ton of liquid metal, mass of on-loading scrap considered with its burn-off.

$$G' \approx 1.05 \text{ x } G, T. \quad (7)$$

$$G' \approx 1.05 \text{ x } 50 = S2.5 \text{ T.} \quad (8)$$

According to Russian standard 7206-80 mass of liquid metal G and primary (first) slag Gm∧ must be contained in the basin of EAF, limited internal plane and horizontal plain, laid through the wing of working window Volume of metal basin of furnace V equal to:

$$V = a.G + BG/C \quad (9)$$

Where a=average volume of liquid steel with temperature of melting=0.235-0.145 m^3/ton, we used 0.14 m^3/ton. B=mass of slag from part of mass of metal 0.07-0.10, we used 0.085. C=density of liquid slag 2.8 - 3.2 ton/m^3 we use 3 ton/m^3. V=0.14 + 0.085 X 50/3 =8.42 m^3 . The depth of the basin h is function of its volume and non-dimensional relations f and m.

$$h = \left[\frac{12 \text{ X } V}{\pi[(3-1.5 \text{ X } f)m^2 - 6(1-f)m + 2(2-3 \text{ x } f + 2 \text{ x } f)]}\right]^{1/3} \quad (10)_2$$

For furnace high powered with water-cooling system, the bottom must be flat with availability of big height of thickness of liquid metal by melting first well in the budding. f=0-0, 1 here we use f=0. The relation m=d_1/h is defined as value of geometrical furnance. For active EAF, the value is formed within the limit of m=3,5-5.5 and we used m=4.

The more the value of m, the more the relative glass plane of the slag, which is capable of penetrating volumetric processes at the boundary of metal-slag. However, when m > 5.5 then the condition of heating the budding and liquid basin at the perriveral, not appropriate, the size of furnace increases and the heat loss becomes bigger. Than,

$$h = [\frac{12 X V}{\pi[(3 - 1.5 X f)m^2 - 6(1 - f)m + 2(2 - 3 x f + 2 x f^2)]}]^{1/3} = 1.047m$$

Furnace with high powered transformers has less height of free surface practically the cylindrical cover, less size of working window. In them assumed non-cylindrical loadings of slag forming materials. Dimension of furnace is defined by the formula:

$$h_1 = (1 - f) x h \quad (11)$$

$$h_1 = (1 - 0) x 1.047 = 1.0475 m$$

$$h_2 = h - h_1 = 1.0475 - 1.0475 = 0$$

$$d_1 = m x h = 4 x 1.0475$$

$$\Delta h = B x h; \text{ where } B = 0.10 - 0.12 \text{ for } \gtrsim 50 \text{ ton.}$$

Mass of on-loading scraps G' changes with consideration of its burn off G' = 52.5 ton.

In accordance with OCTT7206 = 80 EAF must be loaded at a line with scrap of density not less than 1.4 ton/m^3. By overloading the scrap from the loading basket into the furnace, loading density of lom reduces up to 20-30%. if density of metal lom in the basket equal to 1.4 ton/m^3, then after loading into the furnance, density reduces to 1.0 - 1.1 ton/m^3. From here it follows:

$$\frac{G^F}{v_{p.п}} = 1.1 \text{ ton/m}^3 \quad (12)$$

Where G/$v_{p.п}$ = volume of limited internal plane of the "(noga)" body, the internal wall of the furnance and horizontal flat surface project through the bottom of fixed ring bottom of furnace.

We define $v_{p.п} = \frac{\pi.h1(d1^2 + d1 \text{ x } d2 + d2^2}{12} + \frac{\pi(k - k'' - \Delta h)(D2^2 + D1D2 + D1^2)}{12} + \frac{\pi \text{ x } D2^2 \text{ x } K''}{4} + Gm A/\gamma$

$$D_1 = d_2 + 2\Delta h = 4.19 + 2 x 0.1152 = 4.42 m$$

$$d_2 = d_2 + 2h_1 = 4.19 - 0.0475 = 2.095 m$$

$$\alpha = 40^0 - 47^0 \text{ accepted } 45^0$$

$\beta = 25^0 - 30^0$ accepted 45^0

For G = 50 accepted A = 0.45 - 0.50

$K = A \times D_1 = 0.48 \times 4.42 = 2.122$ m

$K'' \leq (0.15 - 0.2)(K - \Delta h)$

$K'' = 0.18(2.122 - 0.1152) = 0.361$ m

$M' = 0.15 \text{ X } D_1 = 0.15 \text{ X } 4.42 = 0.663$ m

$N' = (1.10 - 1.30)m' = 1.2 \text{ X } 0.663 = 0.7956$ m

$DN' = 0.14 \text{ X } M' = 0.14 \text{ X } 0.663 = 0.093$ m

$D_2 = D_1 + K'' \text{ X } 2 \text{ X gtB} = 4.420 + 0.361 \text{ X } 2 \text{ X tg}45^0 = 0.663$ m

$L' = L_{uz} + L_{MeT} + L_{Bogh} = 0.05 + 0.025 + 0.14 = 0.215$ m

$DK = D_2 + 2L' = 5.0366 + 0.215 = 5.466$ m

$\Delta K = (0.11 - 0.13) \text{x } D_K = 0.12 \text{ x } 5.466 = 0.656$ m

$P = 0.02 + 0.02 + 0.065 + 0.466 + 0.130 = 0.681$ m

$d_0 = d_{эл} + \Delta d, \Delta d = 0.0 - 0.04$ m

$d_0 = 300 + 10.0 = 310\text{mm} = 0.31\text{m}$

$d_0 = q \text{ x } D_1 = 0.35 \text{ x } 4.42 = 1.546\text{m}$

$$v_{p.п} = \frac{3.14 \text{ x } 1.0475\,(4.19 \text{ x } 2.095 + 2.095^2)}{12} + \frac{3.14(2.122 - 0.361 - 0.11)\,(5.0366^2 25.3673 + 4.42 \text{ x } 5.0366 + 4.42^2)}{12} +$$

$$\frac{3.14 \text{ x } 5.0366^2\, 0.361}{4} + 4 = 48.62\text{m}^3$$

$$G'/\, v_{p.п} = \frac{52.5}{48.62} = 1.07.$$

Let us try reduce the heat loss by reduction of the area of water-cooling element of working plane. We have to find new volume ($v_{p.пHoB}$) of working plane, accepted that on-loading 65% mass of scrap at a go and (35%) scrap in dose after each portion of melting, we will then assume that density of loading metal is 1.07 ton/m^3.

$$1.07 = \frac{0.65 \text{ x } 52.5}{v_{p.пHoB}},$$

From there we find $v_{p.\sqcap HoB} = \frac{0.65 \times 52.5}{1.1} = 31.02\ m^3$

$$\Delta v_{p.\sqcap} = v_{p.\sqcap} - v_{p.\sqcap HoB} = 48.62 - 31.04 = 17.58\ m^3$$

$$\Delta v_{p.\sqcap} = \frac{\pi \times D2^2 \times \pi K"}{4};\ \Delta K'" = \frac{4 \times \Delta V p\sqcap}{\pi \times D2^2} = \frac{4 \times 17.58}{3.14 \times 5.03662^2} = 0.883\ m$$

$\Delta K'"$ =symbolizes how much we reduce height five internal wall (K). Now we can defne the area of internal plane for both conditions ($\Delta v_{p.\sqcap\delta az}$ and $v_{p.\sqcap HoB}$)

$$S_{\delta az} = \frac{\pi \times D2^2}{4} + \pi \times D_2 \times K = \frac{3.14 \times 5.0366^2}{4} + 3.14 \times 5.0366\ (2.122 - 0.883) = 39.51\ m^2$$

Assuming that heat loss power will be reduced proportional to the area of water cooling elements of the furnance. For the basic variant, $U_D = 110.2$ (see Table 3), a = sum of fall in voltage at anode and cathode equals a=40V, B=Fall in voltage on 1 mm of arc (gradient of fall in voltage) V/mm accepted β = 1 x 10^3.

$$L_{g\delta az} = \frac{110.2 \times 40.0}{1 \times 10^3} = 0.07m = 7.02\ cm$$

Dependence of lenght of arc on voltage (U_D) is as shown in the Table 1.

Table 1. Dependence of U_D on the length of arc.

$P_{T\sqcap}$, Mw	U_D,, V	L_g, cm
7.707	110.2	7.02
10%	106.5	6.65
30%	98.2	5.82
40%	94.5	5.42

From this table above, we can conclude that reduction of heat loss by increasing slag foam is impossible. By so doing, the lenght of open arc correspondingly reduced and remained always less that the thickness of the slag layer (δ).

Varying the values $P_{T\sqcap}$ from 0.707 to 4.6242 mW, we have calculated electrical and working characteristics on computer and the result is shown in the Figure 1 and Table 2.

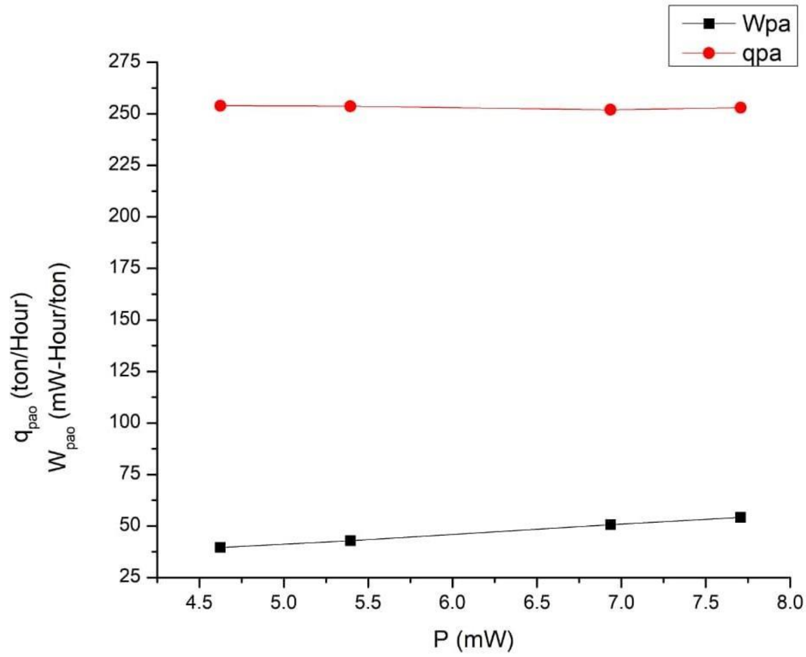

Figure 1. The effect of power loss on the productivity and usage of electric energy

Table 2. Effect of power of heat on the calculation of electric energy and productivity of furnace for refinery period

$P_{TП}$, Mw	I_1, A	$q_{paФ}$, ton/Hour	$W_{paФ}$, mW-Hour	t, Hour/ton
7.707	34934	253.0	0.0542	0.00397
6.9363	33735	252.0	0.0506	0.00395
5.3949	31116	253.7	0.0429	0.00394
4.6242	29932	254.0	0.0396	0.00394

During the variation of power of heat loss, result of calculation of index for the whole smelting is presented in Figure 2 and Table 3.

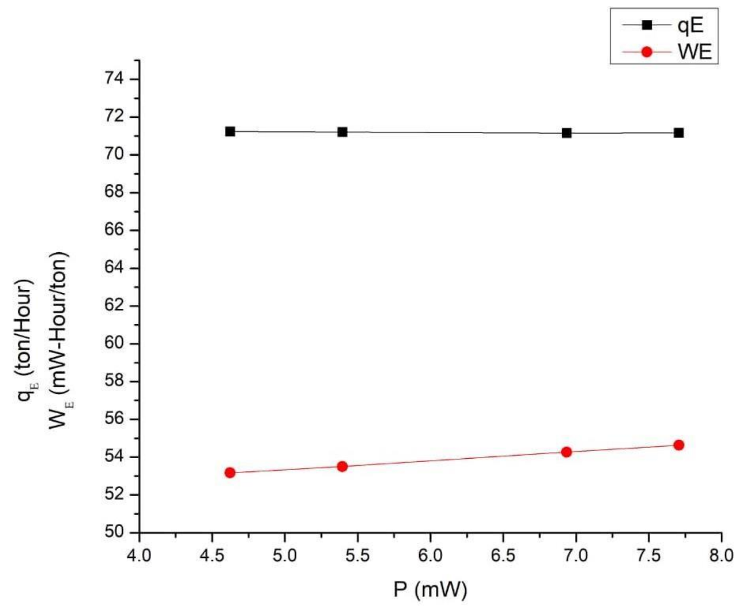

Figure 2. The dependence of productivity and usage of electricity on power of heat loss

Table 3. Effect of power of heat loss on productivity of furnace and usage of electric energy throughout the smelting

$p_{Tп}$	$I_{1PaФ}$	$W_{PaФ}$	Wε	$q_{PaФ}$	Qε
Mw	A	wM-Hour/ton	mW-Hour/ton	ton/Hour	ton/Hour
7.707	61497	0.0542	0.5463	253.0	71.16
6.9363	33735	0.0506	0.5427	252.0	71.15
5.3949	31116	0.0429	0.5350	253.7	71.21
4.6242	29932	0.0396	0.5317	254.0	71.23

The founded equation from the graph has the form:

$W'\varepsilon p_{Tп} = 0.005 p_{Tп} + 0.5089$, mW-Hour/ton.

$q'\ \varepsilon p_{Tп} = 71.335 - 0.02271\ p_{Tп}$, ton/Hour.

Calculated value of usage of electric energy and productivity of furnace on power of heat loss presented in Table 4.

Table 4. Effect of power of heat loss on usage of electric energy and productivity of furnace.

$P_{Tп}$, Mw	4.6242	5.3949	6.9363	7.707
$P_{Tп}$, Wm-Hour/ton	0.5343	0.5386	0.5470	0.5513
$P_{Tп}$, ton/Hour	71.23	71.21	71.17	71.16

Accepted that reduction of heat loss does not demand any other additional expenditure, assumed that reduction of $P_{Tп}$ can be achieved better organization of production and more rational construction of EAF. In that case, there is no more difficult variant calculation.

Expenditure by limit can be defined as follows:

$$CP_{Tп} = \frac{n}{71.335 - 0.02271 P_{Tп}} + (0.0055 \times 0.5089) + A' \quad (13)$$

$$CP_{Tп}.min = \frac{1329.27}{71.335 - 0.0227 \times 7.707} + 13.58\,(0.0055 \times 4.6242 + 0.5089) + 14.938$$

$$= 40.86 \text{ Rouble/ton.}$$

$$CP_{Tп}.min = \frac{1329.27}{71.335 - 0.0227 \times 7.707} + 13.58\,(0.0055 \times 7.707 + 0.5089) + 14.938$$

$$= 41.10 \text{ Rouble/ton.}$$

$$\Delta C_{PTП} = C_{PTП.max} - C_{PTП.min} = 41.10 - 40.10 = 0.2 \text{ Rouble/ton.} \quad (14)$$

limit is shown in the Table 5 and on Figure 3.

Table 5. Effect of power of heat loss on usage of electric energy and productivity of furnace.

$P_{tn,Mw}$	4.6242	5.3949	6.9363	7.707
$C_{PTп}$, Rouble/ton.	40.86	40.92	41.04	41.10

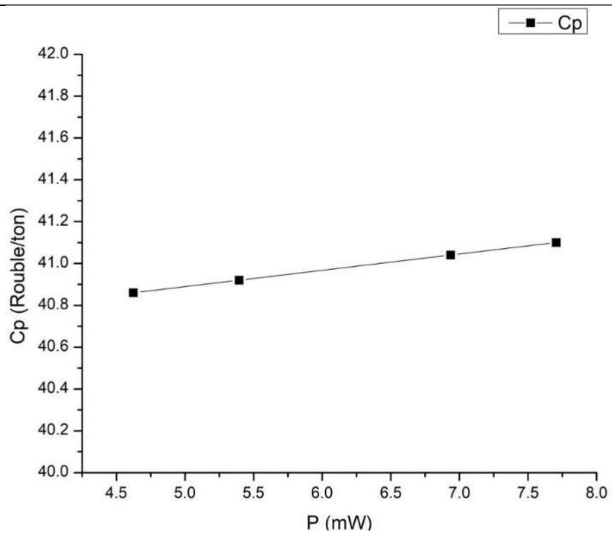

Figure 3. Graph showing the effect of power of heat loss on the cost by limit.

4. Conclusion

From the Table 5, the following conclusions can be drawn: Different between maximum and minimum value of expenditure by limit i.e. CPTп = CPTп.max - CPTп.min = 41.10 – 40.86 = 0.24 Rouble/ton. This means that cost by limit when reduction of PTп by 0.24 Rouble/ton, which is 0.58% of cost by limit. Reduction of power of heat loss from 7.707 to 4.6242 reduce expenditure by limit by 0.24 Rouble/ton.

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