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## Research of heat exchange and efficiency of the arcs in the arc steel-melting furnaces with usual conveyor and loaded

To cite this article: A N Makarov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **552** 012036

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# Research of heat exchange and efficiency of the arcs in the arc steel-melting furnaces with usual conveyor and loaded

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**Abstract.** The analysis of heat exchange and the efficiency of the arcs in the arc steel-melting furnaces with usual conveyor and loaded. For comparison, accepted arc furnace close in power and performance. The analysis revealed that the average efficiency of arcs furnace Consteel ASF-120co 8-9% less than particle ASF-120us. Analysis of the efficiency of the arcs of electric arc furnaces allowed to explain more 8-9% lower specific energy consumption in the furnace ASF-120co compared to the same period in the furnace ASF-120us. Calculation and the analysis of efficiency of various ways of input of heat in a bathtub of metal of ASF-120co and ASF-120us furnaces is performed. The most effective way is introduction of heat by means of electric arches which efficiency is 0,69-0,78. Heating of the metal charge by means of torches of gas-oxygen torches, efficiency of the method 0,45-0,55 is less effectively carried out. Heating of a metal bath by means of oxidation of coke which is continuously entered into slag for foaming of the last is carried out with the efficiency of a way of the method 0,28-0,36.

**Keywords:** electric arc, furnace, steel, torch, thermal radiation, efficiency

## 1. Introduction

The first arc steel furnace (ASF) designed by Consteel was put into operation in December 1989 at the Charlotte plant in the United States [1]. The principle of operation of the Consteel furnace with a capacity of 120 tonnes the following: the conveyor length of 30 m is supplied into the furnace charge at a speed of approximately 6 m/min. Flue gases from the furnace pass through a tunnel with conveyor, heat the mixture to 300°C, resulting in the specific energy consumption is reduced by 40-80 kWh/t. At the time of the filing of the charge in the furnace must be 20-30 tonnes of liquid metal. By 2006, the world was put into operation 22 of the furnace and in the following years their input has continued [1-3].

In 2007, OJSC "Asha metallurgical plant" (AMP) has taken the decision to replace open-hearth production at ASF using Consteel furnace [1]. Furnace ASF-120co was commissioned by the AMP in 2010. The subsequent operation of the furnace Consteel on AMP showed that one of the main advantages of these furnaces over modern furnaces of a usual design of ASF-120us – the smaller specific consumption of the electric power – in 2011-2016 years could not be achieved. Held at the furnace Consteel AMP carrying trunks showed greater 40 kWh/t specific consumption of electricity compared with the same capacity of modern ASF conventional design [4-5].

Loading of furnace charge in the furnace of a usual design is made by means of baskets from which furnace charge from above is loaded into 2 receptions on 60-70 tons. For an explanation of the raised



specific expense of the electric power now in Consteel furnaces in comparison with furnaces of a usual design it is necessary to conduct a research, the including calculations of efficiency of arches and the analysis of a power consumption of ASF for 1989-2016. The results of such research and calculations are given below.

## 2. Calculation and the analysis of efficiency of arches in ASF of a usual design and Consteel

In [6] shows the changes in specific energy consumption in the ASF for the years 1980-2014, use them. In the late 1980's, early 1990's by the heating of the charge consumption of electricity in furnaces, Consteel was less than 80-120 kWh/t compared to furnaces of conventional design, the advantages of the Consteel furnaces compared to furnaces of conventional design was undeniable and their use in the global steel industry has increased steadily [1].

Since the mid 1990's in the production of steel in furnaces Consteel and conventional design using a variety of methods of intensification of the smelting process that led to the reduction of the difference in the index of specific energy consumption in furnaces Consteel and conventional design.

In the 1996-2003's specific energy consumption in furnaces Consteel at work on 100% scrap amounted to 380-410 kWh/t [2,3], in furnaces of conventional design 420-430 kWh/t [6]. In the early 2000's the difference in the specific electricity consumption of the furnace Consteel compared to furnaces of conventional design is reduced to 30-40 kWh/t of steel.

In the 2003-15's continued increase in power density of up to 800-850 kVA/t in furnaces of conventional design, and up to 750 kVA/t Consteel furnaces. The increase in the power input in the furnace led to a further increase in productivity, a decrease in melting time and specific energy consumption. At present, the specific power consumption when operating at 100% scrap in Consteel furnaces is 385-395 kWh/t [5], in furnaces of conventional design 360-375 kWh/t [4]. This phenomenon requires an explanation and can be obtained by analyzing the heat exchange and the calculation and analysis of the change in the efficiency of the arc furnaces of conventional design and Consteel. Technical characteristics of the compared furnaces are given in table. 1.

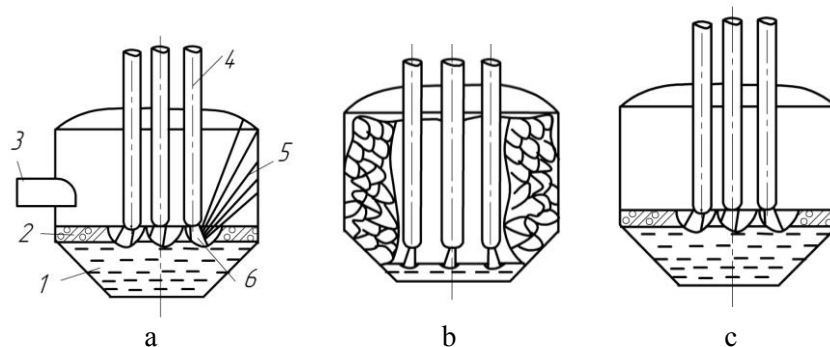
**Table 1.** Technical characteristics of furnaces with conveyor and conventional loading.

Technical characteristics	ASF-120co	ASF-120us
Furnace capacity for production, t	120	120
The rest of the metal in the furnace, t	50	
Transformer power, MVA	90	100
The secondary voltage is linear, V	649-1000	600-1100
The voltage phase, V	375-578	347-636
Arc current, kA	50-70	50-75
Melting time, min	60-62	60
Time under current, min	50	45
Specific electricity consumption, kWh/t	416	375

The average or arithmetic mean of the energy parameters of the furnaces, was found in the results of data processing of a few dozen trunks, are robust indicators of the efficiency of furnaces. To explain increased consumption and total electric energy in the furnace with ASF-120co compared to ASF-120us about the feasible calculation of the average for the melting efficiency of the furnaces arcs. The efficiency of the arc is equal to the ratio of the useful power of the arc  $P_{us}$ , going to heat, melt the metal and slag, to the power of the arc  $P_a$  and is determined by calculating the average angular emission factor of the arc  $\phi_{am}$  on the metal and metal bath [6,7,11]:

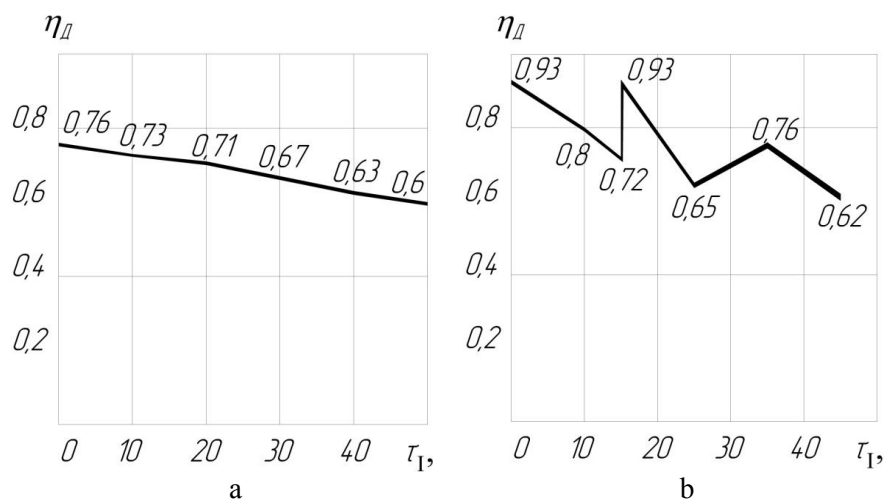
$$\eta_a = P_{us}/P_a = 0,08 + \varphi_{am} \quad (1)$$

According to this method, the efficiency of the arcs of Consteel furnaces and conventional design was calculated, the results of calculations coincided with the results of calculation of the efficiency of arcs described in [6] and [7]. The position of the charge in the compared furnaces is shown in fig. 1a-1c.



**Figure 1.** The working space of the electric furnace ASF-120co Consteel (1, a): 1 - metal bath; 2 - slag; 3 - the front part of the conveyor; 4 - electrodes; 5 - the emission of electric arcs on the walls and the arch; 6 - electric arc; the working space of the electric furnace ASF-120us in the process of melting the charge (1,b),  $\eta_a = 0,93$ , and to the end of melting (1,c),  $\eta_a = 0,65$ .

Let us use the results of calculations of the efficiency of arcs in [6,7] to plot the change in the efficiency of arcs during the operation of Consteel furnaces and conventional design under current. As shown by the results of calculations of the arc efficiency in the furnace ASF-120co [6,7] with a completely immersed in the slag arc, its limit value  $\eta_a = 0,76$ , remaining virtually unchanged with a further increase in the height of the slag layer. (Fig. 2)



**Figure 2.** Change the efficiency of the arc in the furnace ASF-120co (a) and ASF-120us (b) during the operation of the furnace under current

From the analysis of the operation of the Consteel furnaces and conventional design, it is concluded that the most advanced Consteel furnaces in the early 1990's, as a result of the processes of increasing power, productivity, intensification of melting, carried out in the 1990-2000 years in furnaces of compared designs, in 2010 lost their advantages in electricity consumption and productivity compared with conventional furnaces. For comparison, efficiencies of arcs furnaces ASFco and ASFus have been found the arithmetic average of the efficiency of arcs for which data are presented on the chart. The result of calculation of efficiency of arcs to compare furnaces revealed that the average efficiency of the arcs of the furnace ASF-120co equal to 0,68, 13% less than the average efficiency of the arcs of the furnace ASF-120us, is equal to 0,78, which has a decisive influence on the specific energy consumption of furnace ASF-120co, it is 11% greater than the specific energy consumption of furnace ASF-120us.

### 3. Calculation and analysis of power indicators of ASF of a usual design and Consteel

Average for melting  $\eta_{as}$  the steady indicator characterizing energy efficiency of operation of the arc steel melting furnace (ASF). The operating mode of ASF with furnace charge loading by one, two baskets ASFus, surpasses an operating mode of ASF with furnace charge loading in efficiency of heat exchange of electric arches conveyor ASFco. The electric furnace ASF-120us of melting works practically all the time with the big efficiency of arches in comparison with the ASF-120co. More than a half of time of melting in the ASF-120us of an arch burn in a well in furnace charge and their efficiency changes from 0,93 to 0,72 depending on well height. In the furnace of a design Consteel ASF-120co of an arch all the time of melting burn not in a well, and on a liquid metal bath and their efficiency changes from 0,76 to 0,6 depending on slag layer height.

Definition of an average for melting of efficiency of arches of electric furnaces allows to calculate the following average energy performance of melting of ASF-120co and ASF120 us: the average useful specific energy entered into the furnace by arches, average specific useful energy of torches of gas-oxygen torches (GOT), average specific useful energy of oxidation of coke and electrodes. We take data for calculation from the table 2 "Energy balance" [4,8,9], will table results of calculation.

We will define the specific energy which is marked out in  $Q_a$  arches as the difference between a receipt part of specific electric energy of  $Q_e$  and electric losses of  $\Delta Q_e$  of an account part:

$$Q_a = Q_e - \Delta Q_e \quad (2)$$

We will determine specific useful energy of arches by the following expression:

$$Q_{au} = Q_a \cdot \eta_{as} \quad (3)$$

Gas-oxygen torches work 12-15 minutes prior to melting, in calculations accept assimilation of heat from combustion of natural gas in GOT of 55% [8,12], the similar value of average efficiency of a torch is accepted in calculations  $\eta_{gs}=0,55$ . Specific useful energy of a torch of GOT  $Q_{ng}$  it is defined as the work of energy of natural  $Q_g$  gas of a receipt part of power balance on the average efficiency of a torch  $\eta_{gs}$ :

$$Q_{ng} = Q_g \cdot \eta_{gs} \quad (4)$$

For the ASF-120co furnace we summarize the work (4) with specific energy of the warmed scrap. Efficiency  $\eta_{FC}$  specific heat of  $Q_F$  from oxidation of Fe, Mn, Si is equal to unit, all heat is acquired by a metal bath [8, 14].  $\Sigma Q_e$  for melting we determine consumption of electric energy by the furnace as the work of a specific expense of the electric power of  $Q_e$  on furnace capacity by production of metal  $G_m=120 t$ :

$$\sum Q_e = Q_e \cdot G_m \quad (5)$$

$\sum \Delta Q_e$  we determine losses of electric energy by for melting as performing specific electric losses of  $\Delta Q_e$  on furnace capacity:

$$\sum \Delta Q_e = \Delta Q_e \cdot G_m \quad (6)$$

Power of three arches of  $3P_{av}$ , average for melting, is defined as private from division of the electric energy which is marked out in arches  $Q_a$  for operating time of the furnace alive  $\tau_m$ :

$$3P_{av} = \frac{Q_a}{\tau_m} = \frac{\sum Q_e - \sum \Delta Q_e}{\tau_m} \quad (7)$$

We determine the useful power of arches by expression:

$$P_{au} = P_{av} \cdot \eta_{av} \quad (8)$$

For ASF-120 furnaces average current of an arch for melting makes  $I_a = 60 \text{ kA}$ . Arc voltage  $U_a$  and length of arch  $l_d$  is determined by the following expressions:

$$U_a = (3P_{av}/3)/I_a \quad (9)$$

where  $U_{AC}$  – anode-cathode voltage drop,  $U_{AC} = 20 \text{ V}$  [15]; grad  $U_C$  – voltage stress in an arc column, when arcing on a liquid metal bath of grad  $U_C = 0,8$  [6,15,16].

From an account part of the table "Power Balances" [4,8,9] we define specific useful energy for melting of  $Q_{um}$  as the sum of heat content of steel of  $Q_{st}$  and  $Q_{sl}$  slag:

$$Q_{um} = Q_{st} + Q_{sl} \quad (10)$$

Efficiency  $\eta_{OC}$  oxidation reaction by oxygen of coke and electrodes can determine by the following expression:

$$Q_{um} = Q_{au} + Q_{ng} + Q_F + \eta_{cc} \cdot Q_c \quad (11)$$

where  $Q_c$  – energy of oxidation of coke and electrodes, in calculations is used this indicator of a receipt part of "Power balance" [4,8,9].

Also the specific useful energy from oxidation of coke and electrodes of  $Q_{cu}$  coming to a metal bath is determined by the made and calculated  $Q_{um}$ ,  $Q_{au}$ ,  $Q_{ng}$ ,  $Q_F$ ,  $Q_c$  parameters  $\eta_c$ :

$$Q_{cu} = Q_c \cdot \eta_c \quad (12)$$

Have received all necessary expressions for calculation of energy performance of melting in arc steel-melting furnaces.

Results of calculation of average energy performance of melting ASF-120co and ASF-120us furnaces are reduced in table 2.

From results of calculation of parameters of melting stated in table 2 it is possible to draw the following conclusions.

**Table 2.** Average energy performance of melting.

	Parameter	Convention	Unit	ASF-120 <sub>co</sub>	ASF-120 <sub>us</sub>
1	efficiency	$\eta$	-	-	-
1.1	- arc	$\eta_{as}$	-	0,69	0,78
1.2	- torch GOB	$\eta_{gs}$	-	0,55	0,55
1.3	- oxidizing reaction Fe, Mn, Si	$\eta_{FC}$	-	1,0	1,0
1.4	- reactions of oxidation of coke and electrodes	$\eta_c$	kW·h/t	0,28	0,36
2	Specific indicators	$Q$	kW·h/t	-	-
2.1	- electric energy in arches	$Q_a$	kW·h/t	399	355
2.2	- useful energy of arches	$Q_{au}$	kW·h/t	275	277
2.3	- useful energy of a torch GOB	$Q_{ng}$	kW·h/t	59	36
2.4	- useful energy of scrap	$Q_s$	kW·h/t	45	-
2.5	- useful energy from oxidation Fe	$Q_F$	kW·h/t	79	80
2.6	- useful energy from oxidation of coke and electrodes	$Q_{cu}$	kW·h/t	60	47
2.7	- useful energy for melting	$Q_{um}$	kW·h/t	473	440
3	Consumption of electric energy for melting	$\Sigma Q_b$	kW·h/t	49920	45000
4	Losses electric for melting	$\Sigma \Delta Q_b$	kW·h/t	2040	2400
5	Average power of three arches	$3P_{av}$	mW	57,7	56,8
6	Useful power of arches	$P_{au}$	mW	39,8	44,3
7	Average power of one arch	$P_{av}$	mW	19,2	18,9
8	Welding arc voltage	$U_a$	V	320	315
9	length of arc	$l_a$	mm	375	368

#### 4. Results of the analysis of power indicators of ASF of a usual design and Consteel

From results of calculation of parameters of melting stated in table 2 that at close electric and geometrical parameters of arches (arc current, arc voltage, arc length) specific useful energy of arches is also approximately identical and makes for the ASF-120co of  $Q_{au}=275$  kW · h/t, for the ASF-120us of  $Q_{au}=277$  kW · h/t. However, because the efficiency of arches of the ASF-120co is  $\eta_{av}=0,69$ , consumption by the furnace of specific electric energy  $Q_a=399$  kW · h/t and the general electric energy  $\Sigma Q=49920$  kW · h that there are more similar indicators of the ASF-120us, components  $\eta_{av}=0,78$ ,  $Q_a=355$  kW · h/t,  $\Sigma Q=45000$  kW·h respectively. As specific losses with the cooling water in furnaces

are approximately identical and make  $48\text{--}50 \text{ kW} \cdot \text{h/t}$ , the difference of a specific expense of the electric power in the ASF-120co of  $\Delta Q_a = 399\text{--}355 = 44 \text{ kW} \cdot \text{h/t}$  make losses of a heat flow of radiation of arches in free space of the ASF-120co and are spent for heating of waste gases.

The higher consumption of specific useful energy on  $33 \text{ kW} \cdot \text{h/t}$  in the ASF-120co is connected with use for 30-35% of greater mass of lime, a large slag formation and on  $33 \text{ kW} \cdot \text{h/t}$  greater heat content of slag in comparison with the ASF-us. Reaction of oxidation with a lower efficiency at 22% of coke and electrodes in the ASF-120co it is connected with inefficient use of radiation of electrodes in these furnaces. In a receipt part of power balances of melting of furnaces ASF-120co, ASF-120us the radiation of electrodes is considered in a component of balances "Energy of coke and electrodes". In ASF-120 furnaces the power of radiation of each of electrodes is 4 mW of [6] or 20% of the power of arches. In ASF-120co during the whole time of melting electrodes radiate in the free space of the furnace blank by furnace charge. An overwhelming part of thermal radiation of electrodes in furnaces ASF-120co is absorbed by flue gases and the cooling water of panels. Energy of radiation of electrodes in furnaces ASF-120co it is useless it is spent, increasing losses with flue gases and the cooling water.

In the early 1990-ies the specific expense of the electric power in Consteel furnaces was on  $80\text{--}120 \text{ kW} \cdot \text{h/t}$  steel less in comparison with furnace of a usual design. In the early 2000-ies because of the introduction of processes of an intensification of melting steel a difference in a specific expense of the electric power in Consteel furnaces and a usual design it is reduced to  $30\text{--}45 \text{ kW} \cdot \text{h/t}$ . In the 2010's of the furnace of a usual design begin to be in the lead on an indicator of a specific expense of the electric power with value of this indicator on  $15\text{--}35 \text{ kW} \cdot \text{h/t}$  less in comparison with Consteel furnaces that is explained by the higher efficiency of arches of ASF-120us in comparison with ASF-120co.

Power balances of melting and calculation of efficiency of arches of arc steel-smelting furnaces allow to define efficiency of various ways of input of energy in the furnace and designs of furnaces, to predict the total power consumption and consumption of electric energy the furnace.

## 5. Conclusion.

Parameters of arches (power, tension, current, length) of furnaces ASF-120co and ASF-120us are same or similar in value. However electric arches of the ASF-120us are used more effectively with the higher efficiency and bigger useful power, less the consumption of electric energy, common for melting. Heating of furnace charge in the conveyor flue gases in ASF-120co hasn't compensated decrease in efficiency of arches with  $\eta_a = 0,93$  at their burning on a liquid metal bath inside the well to  $\eta_a = 0,76$  at their burning on the metal bath covered with a thick layer of slag.

From all ways of introduction of heat to a metal bath the most effective is oxidation reaction by oxygen of iron and other metals, the efficiency of a way is equal to unit. However energy cost of  $1 \text{ kW} \cdot \text{h}$  of oxidation of iron is 2,37 times more than cost electricity of  $1 \text{ kW} \cdot \text{h}$  [8] because wide use of this way is economically inexpedient. Electric arches which efficiency 0,69-0,78 are in the second place by efficiency of use of heat in furnace. The third place by efficiency of use of heat for furnace charge metal heating in furnace is taken by gas-oxygen torches with the efficiency of a torch 0,45-0,55 [8, 14-16].

The fourth place by efficiency of use of heat for heating of metal bath is taken by reaction of oxidation of coke and electrodes with efficiency 0,28-0,36. In furnace ASF-120us efficiency of reaction of oxidation of coke and electrodes 22% more, than in ASF-120co furnaces that is connected with useful use in furnaces ASF-120us of radiation of electrodes on solid charge. Coke is blown into a metal bath during the whole time of melting for maintenance of foamy slag. At combustion of coke in slag heat is generated, temperature of slag is slightly higher than metal bath temperature, slag transfers heat to a metal bath by thermal conductivity. At the small difference of temperatures of slag and metal the efficiency of heat exchange is small and the efficiency of heat of coke is small,  $\eta_c = 0,28\text{--}0,36$ . At combustion of coke there is an intensive formation of high-temperature gas, gas carries away 64-72% of heat which is formed at coke combustion. As into the ASF-120co furnace enter 65% more coke, than into



the ASF-120us furnace, and amount of flue gases and loss of heat with gases in ASF-120co 73% more than in the ASF-120us. Losses with gases include losses of heat radiated by electrodes.

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