

Chapter 2

Analysis of Technologies and Designs of the EAF as an Aggregate for Heating and Melting of Scrap

Abstract The following issues are considered: the role of hot heel in scrap melting by electric arcs in the furnace freeboard; advantages and disadvantages of furnaces with a single charging and those with a telescoping shell; Specifics of furnace scrap hampering its heating by burners. The possibilities of using different types of burners for scrap heating are analyzed including stationary burners and jet modules as well as slag door, oriel, and roof rotary burners. The data of industrial tests of the process of two-stage melting of scrap in different EAFs with the use of rotary burners without using electrical power in the first stage are given. Under conditions of short tap-to-tap times in modern EAFs the high-temperature scrap heating by burners is impossible. The advantages and disadvantages of EAFs of various types with preheating of scrap with off-gases and melting of heated scrap in liquid metal, including both Consteel conveyer furnaces and shaft furnaces of the Quantum, SHARC, COSS, ECOARC types are considered. In all the shaft furnaces, the scrap preheating temperatures do not exceed 400–450 °C and electrical energy consumption is about the same equal to 300 ± 15 kWh/t. This is explained by the fact that the possibilities of further raising the scrap preheating temperature with off-gases and thereby reducing the consumption of electrical energy are practically exhausted.

Keywords Stationary and rotary burners • EAF types with scrap preheating • Two-stage process

2.1 Melting a Scrap by Electric Arcs. Function of Hot Heel

In a conventional technology, scrap is charged by baskets from the top and placed in a furnace freeboard where it is mainly melted by electric arcs with little involvement of burners and other energy sources. Direct contact of scrap pieces with arcs plasma having a temperature close to 6000 °C provides a high melting rate which increases with increasing power of arcs.

With the increase in EAF's electrical power, the process of the heat with hot heel where a quantity of metal and slag at each tapping is left on the bottom received general use. In high power furnaces, boring-in scrap pile occurs so quickly that the layer of melt is not deep enough when electrodes reach closely to the bottom. Before, in the absence of hot heel, there was a danger of damaging bottom refractory by powerful arcs. This factor restricts increasing electrical power of the furnaces. The hot heel has eliminated the said limitation and allowed increasing electrical power with the aim of further increase in productivity.

In furnaces with hot heel, scrap discharged from the bottom of baskets is immediately immersed into a bath and melted in liquid metal. With increasing the hot heel weight a share of the charge melted in this manner increases. This fact has to be taken into consideration in calculations of melting time of the entire scrap. Operation with the hot heel has also a number of technological advantages such as tapping without slag, early start of bath blowing with oxygen, submerging arcs into a foamed slag, etc. To maintain the mass of metal retained in the furnace at a relatively constant level close to the optimum is a necessary condition for complete and stable enough to use all the advantages of operation with hot heel. For this purpose, furnaces are equipped by sensors which allow controlling a furnace weight varying during the heat and consequently a hot heel weight.

2.1.1 Single Scrap Charging

Recently, EAFs with expanded freeboard size capable of receiving all scrap of about 0.7 t/m^3 bulk density charged by single basket are getting spread. Charging each basket requires roof swinging and current switching off. With short tap-to-tap time, using one scrap basket instead of two leads to a considerable increase in EAF's hourly production. However, the advantages of furnaces with single scrap charging are not limited to that.

Freeboard volume is expanded in such furnaces mainly by means of increasing its height. Greater height of scrap pile in the furnace provides for better scrap absorbing the heat of hot gases, obtained when post-combusting of CO, passing upwards through scrap layer from below. The same can be said about absorbing heat from flames of oxy-gas burners installed in the lower parts of furnace side-walls. Increasing depth of pits bored-in by arcs in scrap also increases the degree of arc heat assimilation. All this increases scrap heating temperature prior to its immersion into the melt, and accelerates melting. At the same time, electric energy consumption is decreased due to the reduction in the time when the furnace is open and loses a lot of heat. Dust-gas emission into shop atmosphere is reduced also while scrap charging. In furnaces of 300–400 t capacity, due to the freeboard height extend, the number of charges is decreased to two per heat.

However, considering the effect of increasing the furnace freeboard height on the utilization of heat in it, it should be taken into account that sidewall area is increased and, consequently, heat losses with cooling water are increased as well. To reduce

these losses, measures are taken to increase the thickness of skull layer on the sidewall panels. For instance, Danieli Company uses panels consisting of two layers of pipes. The pipes of the internal (with respect to freeboard) layer are spaced apart much wider than in the external one. That facilitates formation of thicker skull layer and its better retention on the pipes. As freeboard height is increased considerably, electrode stroke and their length are respectively increased as well, thus increasing the probability of electrode breaking. To prevent breaking the rigidity of arms and of the entire electrode motion system should be increased. The lateral surface area of electrodes as well as their wear due to oxidation, which is about 50% of the total electrode consumption, is increased. Taking into consideration all these factors it can be assumed that furnaces of no more than 180 t capacity are most suitable to realize a single scrap charging.

It should be paid attention to the fact that a freeboard height required during the scrap charging and the initial melting stage comes into conflict with an optimum height after the flat bath formation when this height should be significantly shortened in order to reduce heat losses. In EAFs with a single charging this contradiction is considerably enhanced.

2.1.2 Telescoping Shell

In order to eliminate the above drawback of single charging furnaces it is necessary to periodically during the heat reduce the freeboard height down to a minimum in the melting end. An EAF with a variable freeboard height has been developed by the Company Fuchs Technology AG. In this furnace, the height reduction is achieved by means of lowering of the roof. The main advantage of this design is that when single charging it allows using a lower-cost scrap with lower bulk density at lower heat losses with water. Operation of such a furnace in a mini-mill in Turkey has shown the ability to reduce a scrap density to 0.55–0.60 t/m³ while reducing electrical energy consumption by about 2%. It should be noted that in furnaces with scrap charging by separate portions into a liquid bath, Sect. 2.2, there is no necessity to vary the freeboard height in the course of the process.

2.2 Heating a Scrap by Burners in the Furnace Freeboard

2.2.1 Specifics of Furnace Scrap Hampering Its Heating

In EAF, as a rule, the cheapest light scrap is used. It usually has a low bulk density of 0.6–0.7 t/m³. Such a scrap consists mostly of lumps with relatively small mass and thickness. The length and shape of these lumps vary widely. The denser, cleaner and more expensive scrap is used in converters which are not suitable for

melting light scrap. Intent of metallurgists to use cheap scrap in EAF is determined by the fact that cost of scrap accounts for approximately 70% of total cost per heat of materials, energy and personnel.

Depending on the source of scrap supply and the method of its preparation for melting the thickness of scrap lumps varies from a few millimeters (sheet busheling) to 100–120 mm. Internal thermal resistance of such lumps is so low that each single lump can be heated at any practically achievable rate. The temperature difference between the surface of a lump and its centre remains negligible and can be ignored. This is not true for ladle skulls, trimmings of large ingots and other similar materials which are heated through quite slowly, and therefore their use should be avoided.

Though the scrap for EAF is preselected, it always contains some amounts of rubber, plastics and other flammable organic materials including oil. The chips from metal cutting machines are especially contaminated with oil. Oil and other flammable contaminants present in the scrap emit a lot of heat while burning out. This causes quite undesirable consequences. Even when moderate-temperature (1300–1400 °C) flame and gas is used for pre-heating of scrap, pockets of burning and melting of small fractions can be formed in the heated layer. When this occurs, the separate scrap lumps can be welded together forming so called “bridges” which obstruct the normal course of the melting process.

In the temperature range 400–600 °C oil and other organic materials contained in the scrap sublimate and burn releasing badly smelling toxic gases so-called dioxins, which requires serious measures of protection of the atmosphere of a shop and as well as environmental protection. At temperatures higher than 800–900 °C the fine scrap is oxidized intensely due to its very large surface area. This decreases the yield. The interaction of combustion products with a highly heated scrap is accompanied by their reduction and fuel underburning. Thus, the specifics of the furnace scrap utilized in EAF create certain difficulties for its heating, especially for the high-temperature heating.

2.2.2 Stationary Burners and Jet Modules

Low-power oxy-gas burners are widespread in EAFs. Unit power of such burners does not exceed 3.5–4.5 MW. They are installed in the wall panels, usually about 500 mm above the bath sill level, as well as in the oriel covers and in the slag doors. In the past, three sidewall burners used to be installed in the furnace in the so-called cold zones between the electrodes where the scrap melting required longer time. The sidewall burners equalized the temperature field along the whole perimeter of the furnace. The oriel burners eliminate the cold zone at the oriel, and the door burners do the same at the slag door sill area. The latter makes possible an earlier metal sampling and temperature taking, which allows shortening a heat. As burners had low unit power their use did not significantly affect electrical energy consumption.

Further practice has led to understanding the necessity of increasing the fuel consumption in the burners not so much for the purpose of saving electrical energy as for intensification of the process. With tap-to-tap time being continuously reduced, this required a significant increase in the power of the burners. However, all attempts made in this direction have not given positive results. At present, unit power of burners, due to the reasons discussed in detail below, remains at the same level as 30–40 years ago. Therefore, in order to increase overall power of the burners, the number of burners has been increased. The number of burners in the furnaces reached six to nine, and in some cases even to 12.

Despite the increase in the number of burners, specific consumption of natural gas in the furnaces did not grow significantly. Usually, it does not exceed 8–10 m³/t. This is a result of the further reduction of the tap-to-tap time and, correspondingly, burners' operation time. The effectiveness of the burners did not change as well. As before, they ensure reduction of tap-to-tap time and electrical energy consumption by not more than 6–8%.

The majority of burners under consideration despite a furnace size and their location are similar in general principles. Their design provides for intense mixing of gas and oxygen partially inside the burner and mostly close to its orifice. When used for scrap heating, the burners operate with oxygen excess coefficient of approximately 1.05. Usually, they form a narrow high-temperature flame. Initial flame speeds are close to the sonic speed or exceed it; maximum flame temperatures reach 2700–2800 °C.

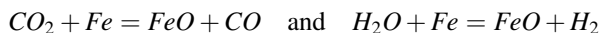
Heating of liquid bath with burners is ineffective. However, small amounts of both gas and oxygen have to be supplied to the burners to maintain the so-called pilot flame. This allows to avoid clogging of the burner nozzles with splashed metal and slag. These forced non-productive consumptions of gas and oxygen noticeably worsen burners' performance indices.

Let us review the causes hindering the increase in power of stationary burners. During the operation of these burners, the direction of flame remains constant. Burner flames attack the scrap pile from the side, in the direction close to radial. The kinetic energy of the flames is low due to their low power. Penetrating into a layer of scrap these flames quickly lose their speed and are damped out. Therefore, their action zones are quite limited.

Since emissivity of oxy-fuel flame in the gaps between the scrap lumps is low, heat from flames to scrap is transferred almost completely by convection. With convection heat transfer, the amount of heat transferred to scrap per unit time is determined by: the surface area of the scrap lumps surrounded by gas flow; the speed of gas flow which determines the heat-transfer coefficient; and the average temperature difference between gases and heat-absorbing surface of the scrap. In the action zone of the burners, at high temperatures of oxy-gas flame the light scrap is heated very quickly to the temperatures close to its melting point. Then the scrap settles down and leaves the action zone of the flame which loses the convective contact with the scrap. In the course of the burners operation, the area of the heat-absorbing surface of the scrap lumps and the temperature difference between the scrap and the flame diminish progressively. The heat transfer remains high only

during a short period after the start of the burners operation. Then the heat transfer reduces gradually and finally, drops so low that the burners must be turned off, as their operation becomes ineffective.

Besides, potential duration of burners operation is also limited by the physical-chemical factors. At the scrap temperatures approaching 1450 °C and especially during the surface melting of scrap, the rate of oxidation of iron by the products of complete combustion of fuel sharply rises. In doing so, the products of fuel combustion are reduced to CO and H_2 according to the following reactions:



The fuel underburning increases, and CO and H_2 burn down in the gas evacuation system. The temperature of the off-gases rises sharply which, along with the other signs of reduced effectiveness of the burners operation, requires turning the burners off.

The described above processes in the scrap pile attacked by a narrow high-temperature flame explain comprehensively the futility of attempts to increase the power of considered burners. In accordance with well-known aerodynamic principles, the length and the volume of the flame and, therefore, its action zone increases insignificantly as the power of oxy-gas burner increases. As a result, the critical temperatures causing fuel underburning and settlement of the scrap in this zone are reached in a shorter time. Respectively, approximately proportionally to the increase in power of the burner, the potential effective burner operation time is shortened, whereas the amount of heat transferred to the scrap increases insignificantly. Only a relatively small portion of scrap pile is heated, which has little effect on energy characteristics of the furnace.

In addition to burners the tuyeres for oxygen bath blowing and injectors for carbon powder injection into the bath to form a foamed slag and reduce FeO were also installed in sidewall panels of EAFs. As a result of the improvement of these systems, they were combined in multifunctional devices, the so-called jet modules. All structural elements of the modules are usually placed in water-cooled boxes protecting these elements from high temperatures as well as from damage during scrap charging. The boxes are inserted into the furnace through the openings in the sidewall panels, which considerably decreases the distances from the nozzles of the burners and from injectors to the bath surface. There is a wide variety of design versions of the jet modules. The advent and development of this direction is associated with the PTI Company (USA) and with the name of V. Shver.

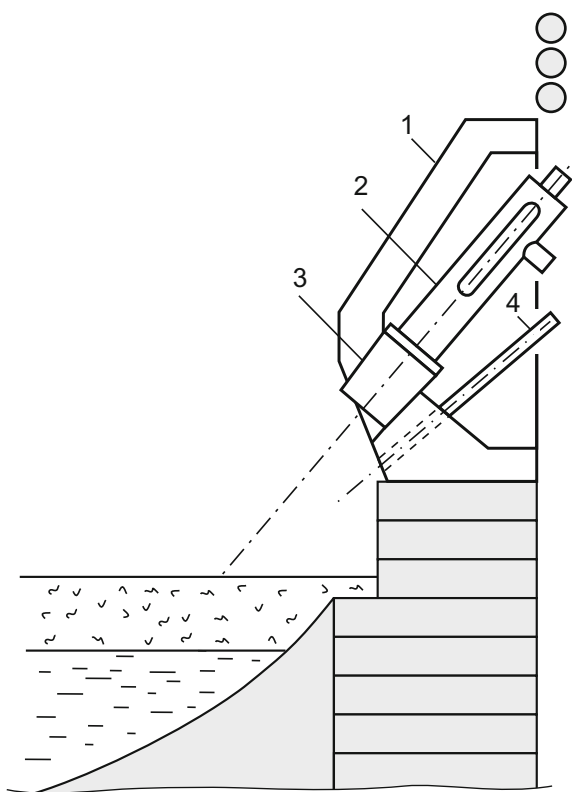
Let us examine the arrangement of the module by the example of a typical design of PTI. Due to a higher durability this module compared to other modules can be installed closer to the sill level. Thus, a distance from the oxygen burner nozzle to metal surface does not exceed of 700 mm. Reducing oxygen jet length improves oxygen efficiency. This is a substantial advantage of the PTI module. Further, this design and the similar ones have gained wide acceptance in many countries around the world.

The PTI module contains the water-cooled copper block (1) in which the oxy-gas burner (2) with water-cooled combustion chamber (3) and the pipe (4) for the injection of carbon powder are located, Fig. 2.1. The burner (2) has two operating modes. In the first mode, it is used as a burner for heating of scrap and operates at its maximum power of 3.5–4.0 MW. The gas mixes with oxygen and partially burns within the combustion chamber (3). At the exit from the chamber, the high-temperature flame is formed, which heats and settles down intensively the scrap in front of the burner. The combustion chamber protects, to a considerable extent, the burner nozzles from the clogging by splashes of metal and slag.

In the second operating mode, the burner is mainly used as a device for blowing of the bath. The gas flow rate considerably decreases, and the oxygen flow rate sharply increases. In this case a long-range supersonic oxygen jet is formed. In this mode, the function of the burner alters. It is reduced to the maintenance of the low-power pilot flame. This flame shrouds the oxygen jet increasing its long range, prevents flowing of the foamed slag into the combustion chamber, and protects the nozzle of the burner from clogging as well.

The burner is controlled by a computer which switches its operating modes in accordance with the preset program. Immediately after scrap charging, the first

Fig. 2.1 Jet module
(designations are given in the text)



mode is switched on. In several minutes, it is switched to the second mode. The highly heated scrap can be cut by oxygen considerably easier than cold scrap. Therefore, the preliminary operation of the burner in the first mode greatly facilitates penetration of the supersonic oxygen jet through the layer of scrap to the hot heel on the bottom. This ensures the early initiation of the blowing of the liquid metal with oxygen, which is the necessary condition for achievement of high productivity of the furnaces. While the upper layers of scrap continue to descend to the level of the burner, the alternation of the operating modes is carried on and is repeated after charging of the next portion of scrap. This considerably increases the effectiveness of the use of oxygen in the initial period of the heat before the formation of the flat bath.

The module operating reliability in a decisive measure depends on durability of the protective boxes and wall panels in the zone of action of the burner. These water-cooled elements operate under super severe conditions. Moreover, the closer to the bath surface, the more severe the conditions. The blow-back of the oxygen jets reflected from the scrap lumps are the main cause of damage of the boxes and panels in the burner zone. Alternating operating modes of the burner reduces this problem, but does not eliminate it completely. In order to increase the durability of the water-cooled elements of the modules, some companies prefer to install them at a greater height, even though this installation increases considerably the length of oxygen jets and reduces the effectiveness of the bath blowing.

It should be emphasized that all the aforesaid concerning limited possibilities to heat scrap by burners of small power relates to the burners of jet modules as well. The need to increase the coverage of the burner on the scrap pile resulted in developing burners with a variable configuration of the flame. During the operation of these burners the shape of the flame could vary widely from the narrow round to a wide flat in a fan shape. Various options of such burners have been tested. However, considerable increase in their efficiency has not been obtained. A slight expansion of the flame coverage on front pile of scrap was compensated by a decrease in the depth of penetration of the flame into the mass of the scrap pieces due to the reduction of its kinetic energy.

2.2.3 Rotary Burners with Changing the Flame Direction

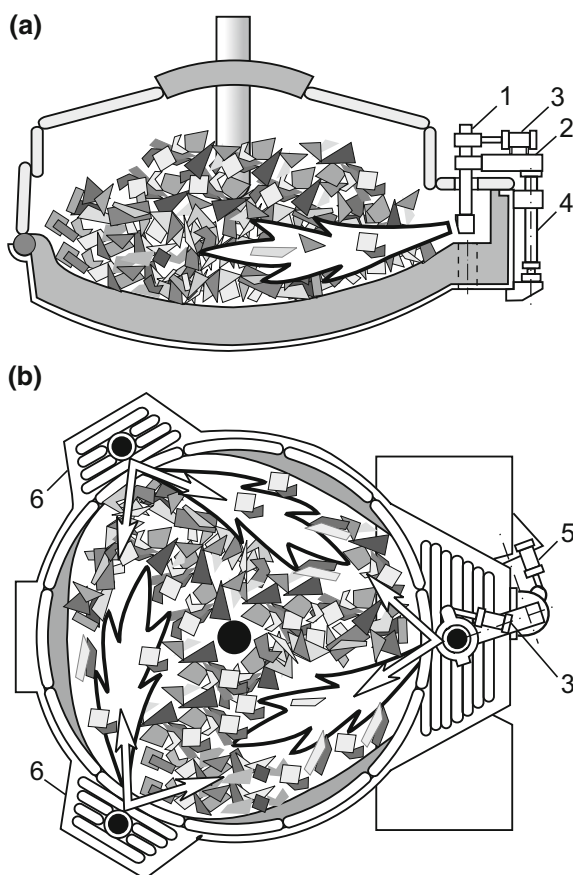
Another way to expand the area of the burner flame impact on the scrap was much more effective. The authors suggested replacing stationary burners with a constant direction of the flame on the rotary burner able to change the direction of the flame over a wide range during operation. The rotary burners have the following principle advantages. Moving flames from those already heated to the relatively cold zones of the scrap allows to increase by several times the effective power of the burners without shortening their operation time. High kinetic energy of the high-powered flames allows them to penetrate through the scrap pile down to the bottom. In this case, the heating gases pass the maximum distance in the layer of scrap, which

considerably increases the heat transfer and the fuel efficiency coefficient. A quick and relatively uniform heating of large masses of scrap in the furnace freeboard can be provided by varying the number, location and power of rotary burners. The temperature of the flames of rotary oxy-gas burners has to be relatively low to prevent the intensive iron oxidation when high-temperature heating.

2.2.3.1 Slag Door and Oriel Rotary Burners

Two variants of oriel burners have been developed: for existing EAFs with an oriel tapping and for a new type of furnaces with an additional oriel, Fig. 2.2a, b. As for slag door burners, since great advantages of rotary burners over stationary ones were evident, they from the very beginning of their application were in most cases mounted on the brackets which allowed changing the flame-direction in the course of the heat. The first of these burners were hand operated and later the management was mechanized.

Fig. 2.2 HPR burners in the main and additional oriels of EAF (designations are given in the text). Patent of Russian Federation, No. 1838736 A3



The installation of the burner in the existing oriel is shown in Fig. 2.2a. The water-cooled burner (1) is fixed to the bracket (2). It can be turned in both directions from the mid position around its axis with the help of the hydraulic cylinder (3). The gas and oxygen nozzles of the burner are located on its lateral surface near the lower end, at an angle to the bath. The vertical displacements of the burner are carried out with the help of the hydro-plunger (4) serving as a stand for the bracket (2) fixed to it in a manner allowing the rotation in a horizontal plane. The rotation of the bracket (2) with the burner is carried out with the help of the hydraulic cylinder (5). The cooling and shielding from the radiation when tapping are provided for all the mechanisms including the gas and oxygen lines of the burner.

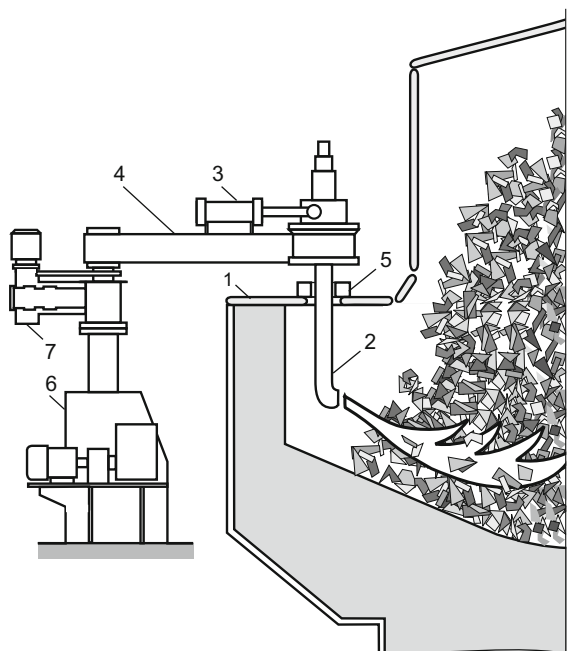
The burner operates as follows. After charging of the first portion of scrap, the burner with the help of the mechanisms of horizontal and vertical displacement is inserted into the technological opening in the cover of the oriel intended for maintenance of the tap hole of the furnace. Then the burner is brought down into the chamber of the oriel to the lowest position, and the flame is ignited. Due to the fact that only insignificant amount of the scrap gets into the oriel chamber, it becomes possible to lower the burner almost to the level of the hot heel. Thereat, the gases pass the maximum distance in a pile scrap from the bottom up.

In the course of scrap heating, the burner is periodically turned around its axis from one end position to another with the help of the cylinder (3). By combining the heating of the layer of scrap from below and the periodic change of the direction of flame in the horizontal plane, the zone of flame action is being enlarged considerably, and the local overheating in the scrap are being eliminated. As a result, the optimum heat-transfer conditions are being ensured as well as, consequently, the possibility to increase sharply the power of the burner, the fuel efficiency and the medium mass temperature of scrap preheating.

As the liquid metal accumulates on the bottom, the burner is pulled up so that it does not immerse into the slag. At the end of the heating of the first portion of scrap, the burner is switched off and raised above the oriel cover. This way the nozzles of the burner are protected from clogging with splashed metal and slag with no use of a pilot flame. The operations of heating of each new portion of scrap charged are repeated in the same order. At the end of the heating of the last portion, the burner is raised to the upper position and is swung together with the bracket (2) in the horizontal plane to the off-position on the side of the oriel with the aid of hydro cylinder (5). The technological opening in the cover of the oriel is freed for conducting the maintenance of the tap hole of the furnace.

The use of one powerful oriel burner for heating the entire scrap charge is just enough to small furnaces only. The additional oriels in the form of special niches (6) in the side walls are required to install several such burners, Fig. 2.2b. These niches opened from the side of the bath make free space for the burner installation and for the changing of the flame direction. The number of niches and their positioning in the furnace can be different. The version with one of side niches intended for the installation of a burner is shown in Fig. 2.3. The lining of walls and bottom of the niche is the extension of the lining of the banks and the bottom of the furnace. From the top, the niche is closed with the water-cooled cover (1) with the

Fig. 2.3 Installation of HPR burner in an additional oriel (designations are given in the text)



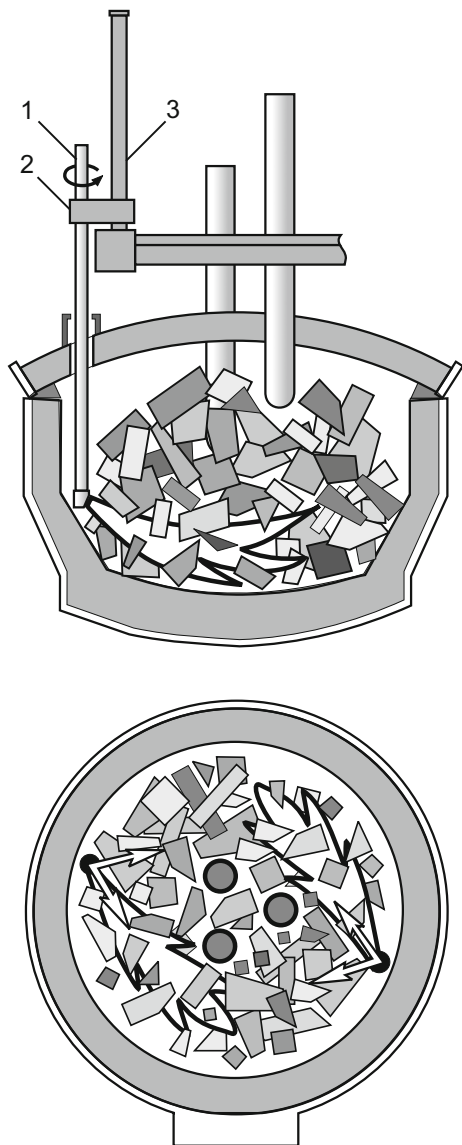
opening for inserting the burner (2). The burner is turned by using cylinder (3) installed on the bracket (4).

The application and the function of the mechanisms of each burner (2) are completely analogous to those of the oriel burner shown in Fig. 2.2. The main difference is that the shaft-type mechanisms with supporting rollers (6) installed on the operating platform of the furnace are used for raising and lowering of the burners. The burner displacement to off-position is carried out with the help of the mechanism (7) turning the bracket (4) with the burner in a horizontal plane. This brings the burner outside the boundaries of the furnace. The mechanisms other than those already described can also be used in the installations of the oriel burners.

2.2.3.2 Roof Rotary Burners

In the second half of the eighties, arc furnaces in a number of Russian plants have operated with the use of a metal charge contained a large amount of heavy rolling trimmings. The high power rotary vertical roof burners called HPR-burners have been developed by the authors for the high-temperature heating of scrap in such furnaces. When charging the heavy scrap by two baskets there is a free space near the sidewalls of the furnace enough for lowering such burners into the freeboard through the roof ports near the roof ring, Fig. 2.4.

Fig. 2.4 Roof HPR burners
(designations are given in the
text)



The roof burners (1) can be lowered and raised as well as turned around the vertical axis up to 60° with the help of the mechanisms mounted on the carriage (2) and on the column (3) along which the carriage moves. The gas and oxygen nozzles are located on the side surface of the burner at an angle to the bath. The flame direction changes within wide limits when the burner is moved along the vertical axis or turned. Changing the flame direction of the burners in the course of the melting period can be carried out either with the help of automatic device

according to the specified program, or manually. In the latter case, an operator directs flames into those zones of the freeboard where the scrap settlement is going slowly. This allows to consider the specifics of the heats and to accelerate the process essentially.

Prolonged industrial trials showed that two roof burners, when being properly controlled, ensure quite uniform heating of the entire scrap pile charged into the furnace. This is promoted by high kinetic energy of the flames of HPR-burners which allows them to penetrate deep into the layer of scrap practically reaching the bottom, as well as by the nozzle configuration providing the retarded mixing of gas and oxygen and reduced combustion temperatures. The burners are lowered into the freeboard only for the duration of their operation. This excludes a necessity to consume gas and oxygen for keeping up a pilot flame.

The tests of the burners were carried out in the old 100-t furnaces with the power of 32 MVA and in the 200-t furnaces with the power of 60 MVA. The furnaces had ceramic walls and roofs. The combined maximum power of two burners in the 100-t furnaces was 25 MW. Two roof burners, 15 MW each, and a slag door burner with the power of 5 MW were installed in the 200-t furnaces. The carried out experiments are of interest as the first experience of the commercially demonstrated technology for heating a scrap by HPR-burners the unit power of which exceeded that of burners currently used by more than tripled.

2.2.4 Two-Stage Scrap Melting. Industrial Testing of the Process

The amount of heat transferred to the scrap by the burners per unit time, i.e. the useful power of the burners P_{br}^* , is determined by the expression:

$$P_{br}^* = \eta_{gas} \cdot \Sigma P_{br} \quad (2.1)$$

η_{gas} gas efficiency coefficient

ΣP_{br} the total power of the burners, MW

The analogous expression for the useful electrical power of the arcs P_{el}^* is:

$$P_{el}^* = \eta_{el} \cdot P_{el} \quad (2.2)$$

η_{el} electrical energy efficiency coefficient

P_{el} electric power of the furnace, MW

Provided that the useful power of the HPR-burners P_{br}^* is close enough to the electrical power P_{el}^* there is a possibility to implement the so-called two-stage melting process. During the first stage the scrap is immediately after each charging heated only by the burners without the arcs, and at the subsequent second stage both

the burners and the arcs or the arcs only are used. Such a process can provide not only the maximum possible reduction in electrical energy consumption due to heating a scrap by burners at the furnace freeboard but also shortening the total duration of the melting period. The latter will be able to take place if reduction in the duration of the second stage of the process $\Delta\tau_2$ exceeds the duration of the first stage τ_1 . The tests of the two-stage process have showed that at the values of P_{br}^* close to those of P_{el}^* the use of HPR-burners allows realizing this condition.

2.2.4.1 Two-Stage Process in 100-t and 200-t EAFs

Parameters of these furnaces and HPR-burners installed on them are given above. The tests were carried out under the actual conditions of current production. The heats with and without the use of burners alternated which substantially eliminated the effect of the random factors. Scrap of each basket was heated and settled down first by the burners without the use of electrical energy, and then by the burners together with the arcs or by the arcs only. Furthermore, the burners were used during the power-off breaks caused by the reasons of organizational nature. During the simultaneous arcs and burners operation, the gas and oxygen consumption in the burners were being decreased.

The effectiveness of the burners operation was evaluated based on a change in the performance indices of the melting period, which, in comparison to the indices of the entire heat, are more closely correlated with the use of fuel for scrap heating. In the old furnaces which operated without treatment of steel in the ladle-furnace units, the electrical energy consumption for the heat and tap-to-tap time strongly depended on the technological factors not associated with heating of scrap by burners. In accordance with common practice, the end of the melting period was determined by formation of the flat bath with the temperature of approximately 1560–1580 °C.

Relative changes in the performance indices of the two-stage process in groups of the heats in the 100-t and 200-t furnaces did not significantly differ. The values of these indices averaged over all the heats are given in Table 2.1.

It should be noted that increasing the stability of arcing on the preheated scrap which was accompanied by an increase in average input power helped to reduce the melting period in the two-stage heats. At the test period of the 200-t furnaces the

Table 2.1 Performances of the two-stage heats

Average burners power as a percentage of average electric power for melting period	92.0%
Burners operation time without arcs as a percentage of melting period	32.5%
Shortening duration of melting period including power-on operation	9.4% 39.0%
Reduction in electrical energy consumption during melting period	37.5%
Gas energy efficiency coefficient η_{gas}	0.70
Average mass temperature of scrap heating by burners	700 °C

durability of the lining did not change and of the 100-t ones that even slightly increased. This indicates that the flames of HPR-burners despite their very high power are not dangerous for refractory and especially for water-cooled elements. Under conditions of the carried out tests with approximately the same power of the burners and arcs, HPR-burners were not inferior to the electric arcs with regards to energy efficiency, Table 2.1.

When testing these burners in the 100-t and 200-t EAFs, the main element of the fuel arc steel melting process namely the high-temperature scrap preheating by means of fuel has been first successfully implemented. Herewith, EAFs themselves acquired during the tests the basic features of the first fuel arc furnaces (FAFs). This was made possible thanks to the low power of transformers and the long tap-to-tap times at the old furnaces. In modern high-power EAFs with very short tap-to-tap time, it is not possible to carry out high-temperature scrap preheating by using fuel in the furnace freeboard as this would require increasing the burners' power to virtually unacceptable values. Nevertheless, the two-stage process is of practical interest for small EAFs with a low transformer power. This is confirmed by the results of testing the two-stage process for 6-t and 12-t plasma furnaces.

2.2.4.2 Two-Stage Process in Plasma Furnaces

Plasma furnaces were utilized in the production of special high-alloy steels and alloys by the method of remelting of clean materials in the neutral atmosphere. To test the two-stage process on these furnaces the slag doors were equipped with two shutters: one regular shutter for insulating the freeboard and the second additional shutter with a rotary oxy-gas burner installed in it. The second shutter had an exit aperture for the combustion products. In order to reduce the flame temperature the burners with a retarded mixing of gas and oxygen are used.

The tests were carried out during the charge melting period which was divided into two stages. At the first stage, immediately after charging of the entire metal-charge, the shutter with the burner was placed in the door of the furnace, and the charge was heated up to the maximum temperature. Then the burner was switched off, the shutters were transposed, the furnace was filled with argon, the plasmatron was switched on, and then the melting and the subsequent heating of the liquid metal were conducted as per conventional procedure without any changes in the electrical regime.

The design of the shutter with the burner allowed to change the flame direction within wide limits in the course of heating the charge and, at the same time, practically completely eliminated the air infiltration into the furnace. With the small dimensions of the bath, the burner ensured the sufficiently uniform heating of the entire charge. The two-stage heats and the regular heats without the use of the burner alternated. This decreased the effect of the random factors.

The entire charge was thoroughly weighed. This allowed to establish with high accuracy that the total oxidation of metal-charge in the two-stage process did not increase despite the presence in the charge of easily oxidized alloying elements.

Table 2.2 Performances of regular (A) and two-stage (B) heats on plasma furnaces

Performances	A	B
Power-on operation time, min	117	52
Electrical energy consumption, kWh/t	840	380

This result is explained by the uniform heating of the charge by the rotary burner as well as by to practically complete absence of free oxygen in the furnace freeboard.

An average burner power during the melting period was 5.5 MW with the natural gas energy efficiency coefficient of η_g equal to 0.5. Relevant parameters of the plasmatron were 2.3 MW and 0.45 respectively. Thus, in this case the burner excels electrical energy source with regard to both power and energy efficiency. The burner operation time τ_{br} was varied within 30 min. At $\tau_{br} = 25$ min gas and oxygen flow rates were 43 and 86 m³/t respectively and average mass temperature of preheating the charge has reached of 1050 °C. The enthalpy of the charge 200 KWh/t corresponds to this temperature. The enthalpy of the completely melted metal, in this case, is equal to 380 kWh/t. Therefore, during the two-stage heats approximately half of the total heat required for complete melting was obtained by the charge from the oxy-gas flame. The main results obtained in the tests on the two-stage process of plasma furnaces are shown in Table 2.2. In two-stage process the furnace power-on operation time and electrical energy consumption are reduced by a factor of 2.2.

The tests conducted revealed another important feature of the two-stage process. Despite a very high unit power of oxy-gas burners which more than twice exceeded the power of plasmatrons, the temperature of the furnace lining only slightly exceeded the temperature of the surface of the scrap and was not higher than 1450–1550 °C. With the arc heating, this temperature was approximately 200 °C higher. This difference is explained by the fact that the temperature of the oxy-gas flame is considerably lower than the temperature of the arc plasma, as well as by the fundamental differences in the laws of heat transfer by radiation and by convection. If the two-stage process is implemented in the EAFs, this feature ensures the decrease in heat losses due to water cooling the wall and roof panels of the freeboard.

In small EAFs, installing the oxy-gas burners whose power far exceeds the transformer power is not too much difficulty. For such furnaces, the established advantages of the two-stage process make it very promising.

2.2.5 *Twin-Shell EAFs*

Twin-shell furnaces are the unit consisting of two furnaces placed next to each other, Fig. 2.5, with common furnace transformer (1) connected by a secondary electrical circuit with a rotary system current conducting arms (2) and with

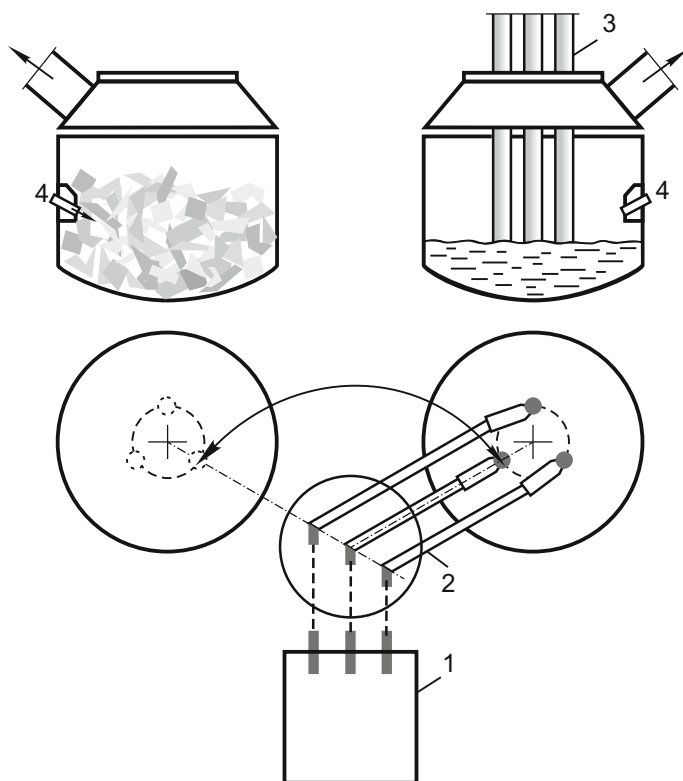


Fig. 2.5 Twin-shell furnace (designations are given in the text)

electrodes (3). This system allows to place electrodes alternately in each of the baths. Several similar furnaces were built in a number of countries, sometimes for the purpose of implementation of the special technological processes such as the units combining the functions of EAF and oxygen converter. This type of units is not discussed here. Both baths of the twin-shell furnaces were equipped with burners for heating of scrap and with devices for oxygen and carbon injection (4). The burners are also required to maintain the temperature of the hot heel at a sufficiently high level during periods of power-off operation.

Technological operations in the twin-shell furnaces are carried out in a certain order. For simplicity sake, one might discuss, as an optimal version, the operation of furnaces with single scrap charging. Charging by two baskets does not change the principle of their operation. While in the first bath during τ all the main technological operations with power-on such as melting preheated scrap, decarburization, heating the melt to a tapping temperature, and tapping itself are carried out, in the second bath for the same time τ_1 all the preparatory power-off operations are implemented namely the operations of closing a tap hole, scrap charging, and scrap preheating by burners.

On completion of the tapping the electrodes are transferred from the first bath to the second one the function of which becomes implementing all the operations with power-on during the time of τ . In this way, the tappings of the heats on the twin-shell furnace occur at regular intervals equal to τ . Maintaining the total duration of all the power-off operations at the same level with that of power-on operations is easily achieved by controlling the scrap heating time which is defined on leftovers.

The prime advantage of twin-shell furnaces is an increase in productivity due to implementing all the preparatory operations at a separate bath in parallel to the basic process operations. This provides considerable reduction in the interval between tappings since the duration of basic power-on operations is significantly shorter than tap-to-tap time of an equivalent single shell furnace.

The second important advantage of twin-shell furnaces in comparison with single shell ones is the presence of a quite long period of time to preheat scrap by burners as the total duration of the rest of preparatory operations is significantly shorter than τ_1 . The scrap preheating reduces electrical energy consumption.

A significant rise in the cost and complexity of the design as well as an increase in maintenance costs are substantial shortcomings of twin-shell furnaces which interfered with their spread.

2.2.5.1 Twin-Shell Shaft Furnaces

As it noted earlier, heating the pile of scrap filling the furnace freeboard by means of sidewall burners had little effect because of non-uniformity of such heating. The most effective device for heating the scrap is a shaft. The highest average mass temperatures of scrap heating as well as the highest values of the gas heat efficiency coefficient close to 0.7 can be achieved when passing the heating gases through the layer of scrap filling the shaft. These considerations resulted in a development of twin-shell shaft furnaces.

In these furnaces, shafts through which scrap is charged into a furnace freeboard are located over roofs of each of bathes. The shafts have no devices retaining the scrap in them. Therefore, after charging a part of the scrap is eccentrically placed in the freeboard. The rest of the scrap fills the shaft.

Burners in twin-shell shaft furnaces can be located in both sidewalls of the freeboard and shafts themselves. Herewith their quantity and total power increase. All the products of combustion are discharged through the shaft which substantially increases the efficiency of the use of burners and provides scrap preheating up to an average mass temperature of about 450 °C. This temperature depends on the power of burners. In Table 2.3 the performances of the recently modified twin-shell shaft furnace are compared with those of one of the very powerful EAFs over the world.

The data in Table 2.3 leads to the following conclusions. Very high (almost the same with the EAF) productivity is achieved in the twin-shell shaft furnace at much lower values of electrical power and the tapping weight (by 1.6 times). Electrical energy consumption decreases by 20%. At identical power of burners installed in

Table 2.3 Performances of 200-t twin-shell shaft furnace and 320-t EAF

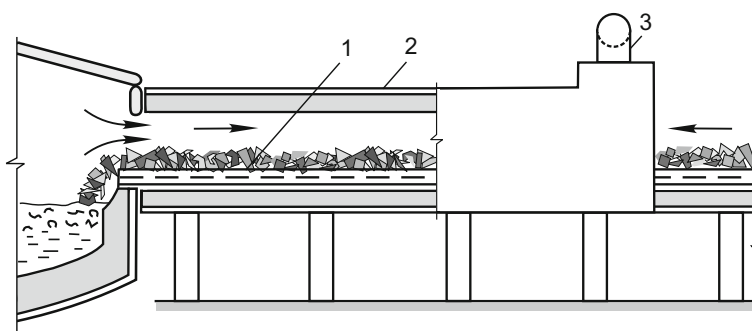
Performances	Shaft furnace	EAF
Tapping weight, t	200	320
Transformer power, MVA	140	240
Interval between tappings, min	36	56
Hourly productivity, t/h	325	343
Electrical energy consumption, kWh/t	290	362
Gas flow rate, m ³ /t	11.7	3.6
Burners power of each bath, MW	32	32

these furnaces this indicates a considerable increase in their efficiency in the shaft furnace. It could be said that the twin-shell shaft furnaces would be promising if it would not be possible to obtain similar or even much better results in the single shell furnaces as well.

2.3 EAF with Preheating a Scrap by Off-Gases and Melting of Preheated Scrap in Liquid Metal

2.3.1 Conveyor Furnaces of Consteel-Type

Due to persistent efforts of Tenova company, conveyor electric arc furnaces Consteel designed by J.A. Vallomy have become considerably widespread. On the late 2013, there were over 40 of these furnaces worldwide. This steelmaking unit combines an electric arc furnace and vibratory conveyor (1) consisting of chutes made of sheet steel. A conveyor is adjacent to a side wall window of an arc furnace from the side opposite to a furnace transformer, Fig. 2.6.

**Fig. 2.6** Consteel furnace (designations are given in the text)

Total length of the conveyor is about 100 m. A part of the conveyor is inside of a refractory-lined tunnel (2) adjoining the furnace. The length of this tunnel is about 30 m. The off-gases leaving the furnace are removed through this tunnel. In the tunnel, the gases move in the opposite direction to the scrap and heat it up. Then the gases are directed through the water-cooled duct (3) into the bag filters. The conveyor chutes located in the tunnel are cooled by water.

Scrap charging into a bath is carried out by special water-cooled chute installed at the end of the conveyor. This chute is filled with scrap at regular intervals, then moved into a freeboard through a window, and the scrap is dropped into a bath. The width of the conveyor depends on furnace capacity and can reach 2.5 m. A furnace roof is opened only during the first heat after a furnace scheduled maintenance before which all liquid metal and slag is tapped from the furnace. During this heat, one basket of scrap is charged into the furnace from the top in order to accumulate on the bottom a sufficient amount of liquid metal to start continuous scrap charging by conveyor. During all other heats, the furnace operates with a hot heel and charging is carried out by conveyor only without opening the roof.

The rate of scrap charging into the bath is always kept equal to the rate of scrap melting in liquid metal. As a result, the bath remains flat during the whole melting process. During this period, the temperature of metal is kept at a constant level of 1560–1580 °C. Temperature increase above this level is not recommended in order to avoid sharp drop in durability of the refractory lining of the bottom and the banks of the furnace.

Long experience of operating Consteel-type furnaces showed that the mode of operation with virtually continuous scrap charging into flat bath and melting it in the liquid metal has a number of essential potential advantages such as energetical, technological, and ecological. Let us outline advantages of this mode of operation along with the factors which allow achieving these advantages:

- Shortening power-off furnace operation time and reduction of electric energy consumption. The contributing factors are as follows: elimination of time spent on opening and closing the roof for scrap charging; elimination of heat losses when the roof is open; improvement in conditions for stable maintenance of the foamed slag layer of the optimum thickness at the flat bath; increase in electric energy efficiency due to complete submerging of arcs into the foamed slag during practically the entire heat; the usage of a lined tunnel for scrap preheating by off-gases.
- Reduction of electrode consumption. In the absence of tall scrap column in freeboard, the risk of electrode damage is drastically lower; decrease of the freeboard height, especially in comparison with single charge furnaces, leads to reduction of electrode length and their side surface area, oxidation of which by furnace gases is one of the major factors of electrode wear.
- Increase in yield. The factors affecting yield increase are an absence of scrap oxidation by furnace gases and by flames of the burners, as well as reduction of FeO in slag and of oxidation level of liquid metal; furthermore, as off-gases pass through a conveyor tunnel, the large-size particles of dust containing iron

precipitate and return to a bath with the scrap; also, evaporation of metal does not occur, since the arcs do not contact solid scrap.

- Cost saving on electrical power supply and lowering of requirements for electrical grids. Due to elimination of the stage of unsteady burning of electric arcs during forming of cave in a column of scrap, there is reduction in voltage and frequency fluctuations generated by the arc furnaces in electric grids; this reduces costs on suppression of electrical interference in the grids as well as simplifies electric power supply to the furnaces.
- Increase of durability and service life of the sidewall and roof panels and other water-cooled elements. This is achieved by elimination of direct radiation of electric arcs which are being submerged in foamed slag at all times; simultaneously the risk of dangerous water leaks into the freeboard resulted from burnouts of the elements is significantly reduced.
- Reduction of gas emissions into the atmosphere and of expenditures on capture and purification of the off-gases; noise level reduction. These ecological advantages are achieved due to elimination of non-controlled dust and gas emissions which take place in case of open roof and increase the quantity of cleaned gases by two or three times; and also due to steady low-noise arcing in the foamed slag.

Along with these advantages Consteel furnaces have substantial drawbacks. Low productivity in comparison with that of modern EAFs of identical capacity is main one of them. Relatively slow melting of the scrap in the liquid metal which is the bottleneck of the whole process is a cause of decreasing productivity.

The rate of scrap melting in liquid metal is determined by intensity of convective heat transfer from metal to scrap which depends first and foremost on speed of metal streams flowing over the surface of scrap pieces as well as on difference in temperatures between liquid metal and scrap. Amount of heat Q transferred from liquid metal to scrap per unit time is defined by the following equation¹:

$$Q = \alpha \times F \times \Delta t \quad (2.3)$$

α , kW/(m ² °C)	coefficient of convective heat transfer from liquid metal to scrap
Δt , °C	average difference in temperatures between metal and scrap pieces, per melting period
F , m ² /t	specific surface area of all the scrap pieces submerged into liquid metal

In Consteel furnaces, electric arcs are constantly submerged into foamed slag. They do not have direct heat contact with scrap and do not affect intensity of heat transfer from metal to scrap. The arcs participate in scrap melting only indirectly by maintaining metal temperature at a required constant level. Given a furnace capacity, such melting mechanism excludes the possibility of increasing melting

¹This process is examined in detail in Chap. 3, Sect. 3.1.

rate by increasing the power of arcs. The latter must strictly correspond to the scrap melting rate which does not depend on the power of arcs. Thus, the power of arcs does not determine scrap melting rate, but, on the contrary, scrap melting rate determines the maximum permissible power of arcs which must not result in overheating of metal. In the EAFs, such a limitation of the electric power does not exist. As the arc power rises, both melting rate and hourly productivity of the furnaces increase.

In the modern EAFs, the scrap melting process may be divided into two periods. During the first period, the main body of scrap pile is melted down with the electric arcs in the furnace freeboard above the hot heel surface. Plasma of the arcs has a temperature of more than 5000 °C and possesses high kinetic energy. The heat energy of the arcs is transferred to the scrap by both radiation and convection. The intensity of these heat transfer processes is much higher than that in the liquid metal where the difference between a temperature of the liquid metal and scrap melting temperature amounts to 30–40 °C only. The power of the arcs is also higher than that of the Consteel furnaces. Furthermore, in EAFs the oxy-gas burners and the process gases formed during post-combustion of CO in the freeboard contribute to the heating and melting of scrap. At the first period of the scrap melting process in EAFs, all these factors ensure the higher melting rate in comparison with that in Consteel furnaces.

During the second period, upon completion of both forming of the flat bath and submerging of the arcs into a foamed slag, the rest of the scrap melts down in the liquid metal. If any, the mechanism of heat transfer to scrap is the same as in the Consteel process. However, just like in the first period, the rate of melting is considerably higher. It could be explained by the fact that the scrap lumps before submerging into the melt are heated in the EAF freeboard up to a temperature which is much higher than that in the tunnel of Consteel furnaces. Only a small portion of fine scrap placed on the bottom of the basket submerges into the hot heel not being preheated.

An increase in melting rate results in the higher productivity of the moderns EAFs as compared with the conveyor furnaces. This consideration is confirmed by actual data. For the entire range of the furnace capacities from 100 up to 350 tons, the rate of scrap melting in the EAFs is higher than that in the conveyor furnaces by approximately 1.6 times. Although the Consteel process eliminates times expended on upper scrap charging with baskets it does not compensate for such a strong lag of conveyor furnaces behind EAFs in the scrap melting rate. As a result, at identical capacity the hourly productivity of modern EAFs exceeds that of Consteel furnaces by an average of 20–25% [1].

Electrical energy consumption in the conveyor furnaces is approximately the same as or even higher than that of the EAFs operating without scrap preheating [1]. Electrical energy consumption is closely related to scrap preheating temperature. When Consteel furnaces were being developed, it was expected that scrap on conveyor would be preheated by off-gases up to 700–900 °C. Such preheating could have ensured quite considerable electrical energy savings. However, these expectations were not realized. Scrap preheating in Consteel furnaces proved to be

ineffective. Mass average temperature of scrap preheating does not exceed 250 °C on the medium capacity furnaces and is even lower on the 350-t furnaces because of the increased scrap layer thickness (reaching 900 mm). According to energy balance of one of such furnaces, the enthalpy (heat content) of the preheated scrap is 16.4 kWh per ton of scrap. Interpolating between the values of temperature t_s equal to 100 and 150 °C, Table 1.1, Chap. 1, we find that the enthalpy of 16.4 kWh/t corresponds to the temperature of scrap $t_s = 125$ °C. Such low average mass temperatures of scrap preheating in the Consteel furnaces is explained by an unsatisfactory regime of heat transfer from off-gases to scrap in the lined tunnel. The off-gases pass at low rate along the surface of the scrap lying on the chutes. These do not penetrate into the inner layers of the scrap. As a result, only the top scrap layer, which receives heat also due to radiation from the lining, is heated intensively.

In countries like Russia, Norway, etc., operation of the Consteel furnaces during winter time causes considerable difficulties resulting from low scrap preheating temperatures. Getting into conveyor, snow and ice melt in the tunnel heated by gases. Water formed as a result does not have time to evaporate. It flows into the lower part of the conveyor chutes, mixes up with mineral debris contained in the scrap forming mud deposits and along with wet scrap are charged into the bath, which is not safe.

Reduced productivity and the absence of significant electrical energy savings are due mainly to the low scrap preheating temperature. The vibration conveyor does not meet the requirements for high-temperature heating of scrap. All the aforesaid does not allow to consider Consteel furnaces as promising aggregates capable of replacing modern EAFs.

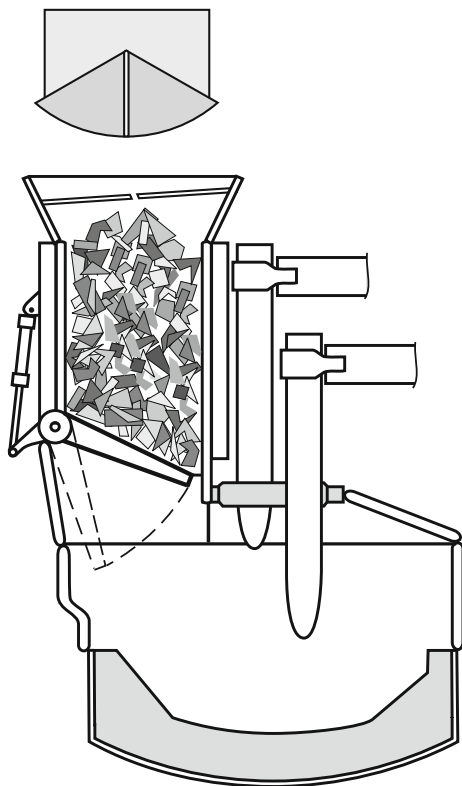
It should be emphasized that the structural disadvantages of Consteel furnaces do not detract from the tremendous significance of the main achievement of J.A. Vallomy and specialists of Tenova as well. They have created a brand new process in EAF and proven the advantages of this process in practice. This process transfers the melting of scrap from the furnace freeboard to a liquid bath which means a new direction of development of EAFs that has a great future.

2.3.2 Shaft Furnaces with Fingers Retaining Scrap

The development of shaft furnaces is associated with the name of G. Fuchs. In the first 90-t shaft furnace the water-cooled shaft installed above the furnace roof did not have fingers retaining the scrap in the shaft. The scrap was charged into the furnace through the shaft. While the lower part of the scrap pile was located on the bottom of the furnace, its upper part was in the shaft. Gases from the furnace were evacuated through the shaft and heated the scrap located in it. As the scrap melted in the furnace, the entire scrap pile settled down. This created the free space in the shaft, which allowed charging of additional portions of the scrap.

Later G. Fuchs has developed and put into operation at plants of a number of countries the furnaces with one row of fingers in the lower part of a shaft, Fig. 2.7.

Fig. 2.7 Shaft furnace with scrap retaining fingers



The scrap is charged into the furnace by two baskets. At the tapping the scrap of the first basket heated by the off-gases during the previous heat lies on the fingers in the shaft. After the tapping the fingers split apart, and the heated scrap is charged into the furnace. After that, the cold scrap from the second basket is charged into the empty shaft. The share of the scrap from the second basket remaining in the shaft is heated by the off-gases passing through the shaft. As the scrap melts in the furnace, the scrap in the shaft rapidly caves in and the shaft clears. This allows shutting the fingers and charging the first basket of scrap on them for the following heat. By the tapping time this portion of scrap is already preheated. With this heating method the overheating and even the partial melting of the lower scrap layer do not create any problems. The melt and the liquid slag formed flow down into the furnace and do not obstruct splitting fingers apart for scrap discharging.

Heating a scrap on the fingers with gases passing through the layer upwards is much more efficient than surface heating a scrap on a Consteel conveyor. This contributes to increasing the average mass temperature of scrap heating and reducing electrical energy consumption. Another advantage of shaft furnaces is that a substantial part of the dust carried out from the freeboard settles down in the layer of scrap. Due to this fact the yield is increased by approximately 1%. Typical performances of shaft furnaces with fingers retaining scrap are shown in Table 2.4.

Table 2.4 Performances of shaft furnace with scrap retaining fingers

Tapping weight, t	135
Tap-to-tap time, min	38
Transformer power, MVA	120
Productivity, t/h	214
Minimum electrical energy consumption, kWh/t	285

There is no reliable data on average mass temperatures of scrap preheating for the finger shaft furnaces. It is known only that the smallest pieces in the lower layer of scrap on the fingers are melted down and fall into the bath in the form of a steel rain. However, this temperature with sufficient accuracy for practical purposes can be estimated by calculation.

2.3.2.1 Calculation

Let us consider the heat balance of the metal bath, namely the metal bath, and not the balance of the entire bath including slag. When melting down a preheated scrap its heat energy is completely absorbed by the liquid metal. Therefore, the average mass temperature of preheated scrap t_s and reduction in electrical energy consumption ΔE_{EL} obtained due to scrap preheating are connected a relationship close to unique:

$$\Delta E_{EL} = c_s \cdot t_s / \eta_{EL} \quad (2.4)$$

c_s average calorific capacity, kWh/(kg °C)

η_{EL} the coefficient of electrical energy efficiency for heating a liquid metal

The product of $c_s \cdot t_s$ is enthalpy of scrap ΔE_{EL} , kWh/t, see Chap. 1, Table 1.1. The η_{EL} coefficient is determined by the following expression:

$$\eta_{EL} = \eta_{SEC.C} \cdot \eta_{ARC} \quad (2.5)$$

$\eta_{SEC.C}$ the coefficient considering electrical energy losses of transformer and the secondary electrical circuit including electrodes

η_{ARC} the heat energy efficiency coefficient of the arcs considering energy losses during the heat transfer from the arcs to the liquid metal.

For the shaft EAFs operating with the flat bath and with the arcs practically continuously immersed into a foamed slag it could be assumed that $\eta_{SEC.C} = 0.93$; $\eta_{ARC} = 0.90$; $\eta_{EL} = 0.93 \cdot 0.90 = 0.84$. Complete immersion of the arcs into the slag does not provide the η_{ARC} coefficient equal to 100%, as sometimes considered. The immersed arcs transfer the heat mostly to the slag, but the slag, though it is mixed with the metal, radiates a considerable portion of the absorbed heat into water-cooled sidewall and roof panels of the furnace. The aforesaid value of the

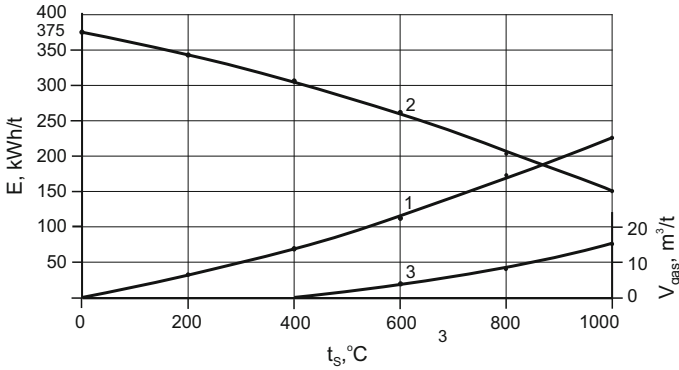


Fig. 2.8 Electrical energy consumption and gas flow rate vs average mass scrap preheating temperature t_s

η_{ARC} and, consequently, the η_{EL} as well should be considered rather somewhat overstated than understated. This fact is confirmed by the investigation of a goodly number of modern EAFs which had shown that during the melting the η_{EL} coefficient ranges from 0.6 to 0.8 [2]. In this investigation, as opposed to the others, it is stated that the η_{EL} coefficient applies to the metal.

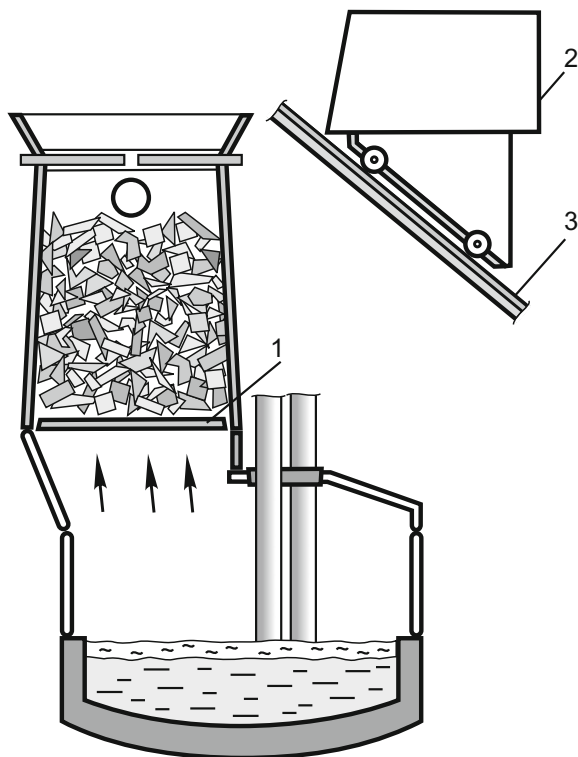
Given $\eta_{EL} = 0.84$, the results of the calculation according to Eq. (2.4) are demonstrated by Fig. 2.8. As the scrap preheating temperature t_s raises, the reduction in electrical energy consumption ΔE_{EL} grows at the increasing rate, curve ΔE . At the $t_s = 1000$ °C, in comparison with the furnace operation without scrap preheating, the ΔE_{EL} reaches 225 kWh/t. Therefore, if we assume that without scrap preheating ($t_s = 0$) the electrical energy consumption EAF is on average of 375 kWh/t, then at the $t_s = 1000$ °C it will decrease to 150 kWh/t ($375 - 225 = 150$). At the $t_s = 800$ °C, the $\Delta E_{EL} = 170$ kWh/t and the electrical energy consumption amounts to 205 kWh/t ($375 - 170 = 205$). Such electrical energy consumptions are unachievable in EAFs operating without scrap preheating.

In operating shaft furnaces with fingers retaining scrap, the minimal electrical energy consumption amounts to about the 285 kWh/t, Table 2.4. Maximum values of ΔE equal to 90 kWh/t ($375 - 285 = 90$) and $t_s = 450$ °C, Fig. 2.8, correspond to this consumption. Thus, it can be assumed that, in accordance with the above calculation, the average mass temperature of scrap preheating does not exceed on average of 400 °C in the shaft furnaces with fingers retaining scrap, Fig. 2.7, when charging two baskets.

2.3.2.2 EAF Quantum

Later design of a finger shaft furnace was persistently improved. The latest variation of the furnace, named Quantum, developed by Primetals Technologies, Germany,

Fig. 2.9 Quantum shaft furnace (designations are given in the text)



along with other innovations comprises a new system of shaft charging and improved design of fingers (1) retaining scrap, Fig. 2.9 [3].

Scrap is charged into the shaft from above by a tilting container (2) moving up and down on inclined elevator (3) rather than baskets with a crane. The container is loaded on scrap yard by the two hoppers. The loading system is automated. It allows covering the shaft with a hood and considerable decreasing uncontrolled gas-dust emissions from the shaft during the charging of scrap. The duration of the complete cycle of charging the next portion of scrap into the shaft is 5 min. This cycle includes the steps of: movement of a container with scrap up to the position of discharging, opening the shaft, scrap discharging, and the movement of the container down to the position of its load with scrap.

As opposite to the fingers shown in Fig. 2.7, in the EAF Quantum the fingers, similar to pitchforks, are introduced into the shaft through its sidewalls. To charge a batch of the preheated scrap into the bath the fingers are pulled out of the sidewalls of the shaft. After charging they are immediately introduced into the shaft to receipt the next batch of scrap. Thus, unlike the system shown in Fig. 2.7 all the scrap is heated on the fingers and not just the first portion. It was assumed that this would allow increasing the average mass temperature of the scrap.

Table 2.5 Basic performances of EAF Quantum [3]

Tapping weight, t	100
Tap-to-tap time, min	36
Transformer power, MVA	80
Productivity, t/h	167
Electrical energy consumption, kWh/t	280–300
Gas flow rate, m ³ /t	4.4

The preheated scrap is charged into the liquid steel bath in several portions. Melting the scrap is realized in flat bath with all the advantages previously discussed, Sect. 2.3.1. The furnace is equipped with two vertical roof tuyeres for oxygen bath blowing.

Basic performances of the 100-ton EAF Quantum in Vepacrus (Mexico) for the first (2015) year of its operation are given in Table 2.5.

2.3.2.3 EAF SHARC

The main feature of a 100-ton shaft DC SHARC-type EAF operating in Hellenic Halyvourgia, Greece, is two shafts disposed symmetric about the central electrode [4]. During operation of the furnace the electrode diameter was increased to 700 mm which is allowed to get rid of breakdowns and lower electrode consumption to 0.6 kg/t. Bottom pin type electrode has a durability of 3500 heats.

The 34 fingers, which can be introduced and pulled together or separately, retain scrap in the shaft. Along with the symmetry of the entire construction such a manner of finger operation provides uniform distribution of scrap on the bath perimeter and uniform melting a scrap as well.

Due to the local conditions the furnace works only for 8 h on weekdays and 13 h on weekends. Because of such an intermittent work schedule the data on furnace productivity and on electrical energy consumption given in Table 2.6 should be considered as a referential data.

Table 2.6 Basic performances of SHARC EAF

Tapping weight, t	97
Tap-to-tap time, min	48
Transformer power, MVA/MW	78/54
Productivity, t/h	120
Electrical energy consumption, kWh/t	290
Gas flow rate, m ³ /t	6.4

2.3.3 Shaft Furnaces with Pushers of the COSS-Type

The off-gas heat efficiency when heating a scrap in a shaft is higher by approximately three times than that when scrap is heated on a Consteel conveyor. On the other hand, continuous furnace operation with the flat bath is an advantage of the Consteel process. In order to combine these both advantages G. Fuchs has developed and implemented shaft furnaces with the practically continuous charging of scrap into the liquid bath. The design of such a furnace named COSS is schematically shown in Fig. 2.10.

A rectangular shaft (1) is installed on the cart (2) next to the furnace. The shaft is connected to the furnace with a short tunnel (3). A sliding gate (4) opens for charging of scrap into the shaft. The charging is carried out with the power-on and does not interrupt the furnace operation. A gas duct (5) is placed under the sliding gate (4). The shaft is lined with the massive steel segments and has no water-cooled elements which could be damaged during the scrap charging. The mass of scrap in the shaft is gauged by the measuring elements on which the shaft rests. This makes it possible to control the rate of charging of scrap into the furnace.

The scrap is charged continuously into the liquid bath in separate portions with the help of the pusher (6) which is moved forth and back by the well protected hydraulic cylinder (7). Such a charging in principle does not differ from the charging of scrap by a vibrating conveyor and allows maintaining a flat bath. Thus, all the

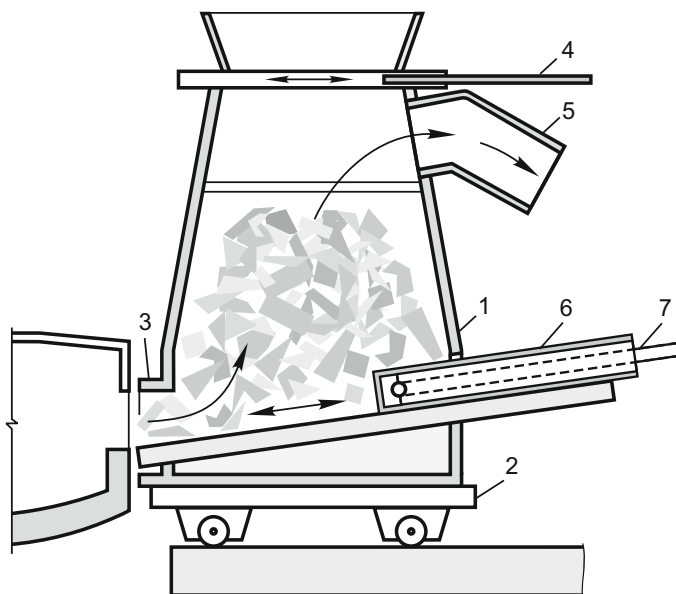


Fig. 2.10 COSS shaft furnace system (designations are given in the text)

above considered advantages of the operation with a flat bath proven by the experience of the Consteel furnaces operation are retained in COSS furnaces, Sect. 2.3.1.

The pusher discharges scrap from the bottom layer which has the highest temperature. Unlike the first finger shaft furnaces, in the COSS furnaces the off-gases heat all the scrap. This made it possible to expect the higher temperatures of heating. However, the data on the electrical energy consumption for the COSS furnaces does not confirm this expectation.

On three such furnaces of 140–150 t capacity with transformers of 80 MVA the minimum electrical energy consumptions were 300–400 kWh/t.² Such electrical energy consumptions correspond to the average mass scrap preheating temperatures of 350–400 °C, Fig. 2.8. Productivity of the furnaces ranged from 125 to 149 t/h, which was significantly lower than that of modern EAFs of the same capacity. This is explained not only by the relatively low melting rate of the scrap in the liquid metal at insufficiently high scrap preheating temperatures but also by the low electrical power of the furnaces.

The pictures of the scrap being discharged from the shaft of the COSS furnace into the window are presented by some publications. These pictures show that the temperature of the surface of scrap pieces at the discharging window can achieve about 700 or 800 °C. However, it should be kept in mind that in this zone the frontal surface of the front scrap layer is exposed to direct heat radiation from the furnace freeboard. Therefore, the mentioned temperatures are much higher than the actual average mass temperatures of the scrap located behind the window. If the actual average mass temperatures could reach 700–800 °C then the electrical energy consumption in these shaft furnaces would be close to rather the 200 kWh/t than to 300, Fig. 2.8.

2.3.3.1 Shaft Furnaces of ECOARC-Type

These furnaces have been developed in Japan regardless of the works of G. Fuchs. Four of these medium-capacity furnaces operate in Japan, one in Thailand, and one in South Korea. The structural scheme of these furnaces is close to the COSS scheme. The main feature of the ECOARC is that the shaft is attached to the furnace shell and forms with it a single whole. In this case, the scrap discharging window of the shaft is aligned with the window of the furnace sidewall without clearance.

In COSS-type furnaces, a large amount of air is infiltrated into the furnace through a gap between it and the scrap discharging window of the shaft. Elimination of this infiltration along with other advantages allowed reducing electrical energy consumption of ECOARC furnaces in comparison with the COSS furnaces. Electrical energy consumption of the 70-t ECOARC furnace of 50 MVA power in Thailand ranges from 310 to 285 kWh/t depending on the scrap quality.

²G. Fuchs's presentation Yekaterinburg, Russia, 2012.

The pusher of the ECOARC furnace is cooled by compressed air which excludes the possibility of high-temperature scrap preheating.

2.4 Factors Hindering Wide Spread of Shaft Furnaces

Shaft furnaces have been operating for more than 20 years in a number of countries around the world. During this time they were considerably improved but still not widely spread. This can be explained by the two factors. Firstly, shaft furnaces as well as Consteel furnaces are much inferior to modern EAFs in terms of productivity due to the long scrap melting time in liquid metal. The reasons for this, in common with the Consteel furnaces, were discussed in detail in Sect. 2.3.1.

Secondly, reduction in electrical energy consumption achieved in shaft furnaces does not compensate decreasing productivity and does not justify the application of the new complex equipment that requires additional maintenance. Of particular note is the fact that a minimal electrical energy consumption of 285 ± 15 kWh/t was almost the same at all shaft furnaces in spite of their rather significant design differences.

The energy consumption of 285 kWh/t has already been achieved 20 years ago at one of the first finger furnaces, although only part of the scrap was heated in the shaft of this furnace [5]. The furnaces of COSS-, Quantum-, SHARC-, and ECOARC-type created much later operate with the same electrical energy consumption. In order to reduce this consumption the scrap preheating to a temperature much more than 400–450 °C is needed. It was not possible to implement such preheating on any of the new shaft furnaces which operate with scrap heating only by off-gases. This leads to the conclusion that a common cause for all furnaces which prevented the further increase in the scrap preheating temperature and the corresponding reduction in electrical energy consumption is the insufficient specific heat power of the off-gas flow P_{gas} , kWh/(t·min). With a short tap-to-tap times this power is practically identical in all shaft furnaces. It is determined by approximately equal consumption of carbon-containing materials, kg/t of liquid steel, which does not depend on the furnace capacity.

Unfortunately, data on P_{gas} is absent. Instead of this key parameter the specific values of heat losses from off-gases Q_{loss} , kWh/t of steel, are given in many publications. According to the data from different authors, Q_{loss} ranges from 80 to 220 kWh/t. It does not specify to which time of power-on operation these values correspond. The value of Q_{loss} cannot substitute for P_{gas} , since it characterizes quantity of heat rather than power of heat flow. Using the value of Q_{loss} , it is impossible to determine average-mass scrap temperature t_s which can be obtained in case of scrap heating by off-gases in a given heating time τ . Determination of scrap preheating temperature t_s requires calculation of the heat power of the off-gas flow P_{gas} .

2.4.1 Calculation of the Maximum Values of the Power of the Heat Flow of Off-Gases and Temperature of Scrap Heating by These Gases in the Shaft

Let us consider the operation of a shaft furnace with flat bath under the following conditions. The only carbon source mainly determining the heat power of the flow of off-gases is coke charged into the liquid bath. The lumpy coke is charged via the opening in the furnace roof. The powder coke is injected into the bath by injectors. The carbon content in the coke is 80%. Carbon contained in scrap is not considered as its concentration does not exceed 0.20%. Further calculations are carried out per a ton of liquid steel.

The total consumption of coke M_{cok} is taken equal to 14 kg/t which are close to maximum consumption used in practice. The total consumption of carbon $M_C = 18 \times 0.8 = 14.4$ kg/t. It is assumed that carbon contained in the coke is oxidized to CO with oxygen injected into the bath with an intensity of $J = 0.9 \text{ m}^3/(\text{t} \cdot \text{min})$. In modern EAFs such intensity is close to maximum. The intensity of CO evolution from the bath (CO flow rate) V_{CO} is determined by the equation: $V_{\text{CO}} = 2 \text{ k} \cdot J, \text{ m}^3/(\text{t} \cdot \text{min})$. The coefficient $k = 0.7$ takes into account that some of the injected oxygen is consumed in the oxidation of iron,³ silicon and manganese, and that a certain amount of O_2 is not absorbed by the bath. The coefficient 2 corresponds to the reaction equation: $2\text{C} + \text{O}_2 = 2\text{CO}$.

$V_{\text{CO}} = 2 \times 0.7 \times 0.9 = 1.26 \text{ m}^3/(\text{t} \cdot \text{min})$. Knowing the amount of carbon M_C in the metal bath and the intensity of CO evolution from the bath V_{CO} , both the blowing time τ required for carbon removal and equal to it the heating time of scrap in the shaft can be determined.

The flow of CO in volume units $V_{\text{CO}} = 1.26 \text{ m}^3/(\text{t} \cdot \text{min})$ corresponds to a flow in mass units $M_{\text{CO}} = 1.26 \times 1.25 = 1.57 \text{ kg}/(\text{t} \cdot \text{min})$, where 1.25 is density of CO, $\rho \text{ kg/m}^3$. According to the reaction equation $\text{C} + 0.5 \text{ O}_2 = \text{CO}$, one kilogram of CO is formed from 0.428 kg of C. To the flow of CO equal to $1.57 \text{ kg}/(\text{t} \cdot \text{min})$ corresponds the flow of carbon $M_C = 1.57 \times 0.428 = 0.672 \text{ kg}/(\text{t} \cdot \text{min})$. The amount of carbon removed from the bath is 14.4 kg. The time of bath blowing $\tau = 14.4/0.672 = 21 \text{ min}$. The time of scrap heating in the shaft is the same.

Further it is assumed that all CO evolving from the bath is sucked into the shaft and only there burns to form CO_2 . Thus, it is assumed that the off-gases consist of CO only, and that all the chemical energy from CO post-combustion evolves in the shaft. These operating conditions of the furnace are idealized. They create the most favor opportunities for reaching the maximum temperature of scrap preheating t_s .

Carbon monoxide introduces both physical q_{ph} and chemical q_{ch} heat into the shaft with scrap.

³It is understood that a part of the resulting iron oxides is not reduced by carbon with evolution of CO and remains in the slag.

$q_{ph} = V_{CO} \times c \times t$, kJ/(t·min), $t = 1570$ °C is temperature of metal during the stage of scrap melting in the furnaces with the flat bath, $c = 1.475$ kJ/(m³ °C) is heat capacity of CO at $t = 1570$ °C. $q_{ph} = 1.26 \times 1.475 \times 1570 = 2918$ kJ/(t·min) or $q_{ph} = 0.81$ kWh/(t·min).

The thermal effect of the reaction $CO + 0.5O_2 = CO_2$ is 3.51 kWh/m³ CO. $q_{ch} = 1.26 \times 3.51 = 4.42$ kWh/(t·min). Heat power of the flow is $P_{CO} = q_{ph} + q_{ch} = 0.81 + 4.42 = 5.23$ kWh/(t·min).

Let us determine the quantity of heat Q introduced into the shaft during $\tau = 21$ min: $Q = 5.23 \times 21 \times 0.9 = 98.8$ kWh/t of scrap, where 0.9 is the yield of liquid steel per 1 ton of scrap. With the heat efficiency coefficient of gases in the shaft equal 0.7, the enthalpy (heat content) of scrap E_S will amount to: $98.8 \times 0.7 = 69.2$ kWh/t. The average-mass temperature of 460 °C corresponds to this enthalpy, Table 1.1. The result of this calculation is in good agreement with the aforesaid estimations of the scrap preheating temperatures in shaft furnaces according to electrical energy consumption. The actual values of t_S should be lower than the calculated ones since in real conditions a significant share of the CO burns even before entering the shaft and gives away some of its heat to the water-cooled panels.

The above calculation as well analysis of the accumulated experience of work and improvement of the EAFs leaves no doubt that the energy of the off-gases is in principle absolutely insufficient for high-temperature preheating of the scrap. To realize this most important element of a new technology an additional more powerful and efficient source of energy is needed. Natural gas should be used as such a source. Dependences of electrical energy consumption on the average mass temperature of scrap preheating were discussed in detail in Sect. 2.3.2.1. Now it is necessary to establish to what extent the increase in this temperature can accelerate the process of melting scrap in liquid metal and increase the productivity of the furnaces as well. Let us examine the results of studies of this process.

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