Chapter 6
Preheating of Scrap by Burners and Off-Gases

6.1 Expediency of Heating

Despite a scrap shortage in some parts of the world and partial replacement of scrap with hot metal or reduced iron, it is still the scrap that both now and in the distant technical perspective should be looked at as the prime metal charge for the majority of arc furnaces. Preheating of scrap is the important technical task and numerous research projects are dedicated to finding a solution to this problem. Preheating the scrap prior to the heat allows increasing the enthalpy of the metal-charge E_{SCR} by ten times and, consequently, sharp reducing the consumption of useful energy required for the heat from E_{MET} to $E_{MET} - E_{SCR}$, Chap. 2, Sect. 2.2, and Eq. (5.5), Chap. 5. The total consumption of useful heat includes the useful consumptions of electrical energy and of other energy carriers. The sum of these useful consumptions decreases by the value of E_{SCR}. The total consumptions of energy carriers decrease respectively. Reduction of electrical energy consumption is usually accompanied by a number of advantages, in particular, by a decrease in electrode consumption. At the same time, power-on time shortens almost directly proportional to the decrease in the required consumption of the useful heat, and productivity increases accordingly. This assures the same or close productivity level of EAF while its electrical power can be significantly reduced.

Scrap preheating is carried out by fuel energy or thermal energy of off-gas which include chemical energy of its combustible ingredients CO and H_2. Compared to using heat of off-gases for getting hot water or steam, heating of scrap is much more efficient option since return of lost heat straight back to the technological process assures not only reduced energy consumption, but also a significant increase in productivity of EAF.

If natural gas or other fuels are used for heating of scrap, then the economy of this process depends both on price level of different energy carriers and on the ratio of the energy efficiency coefficients η for different forms of energy. However, since an increase in productivity decreases operational personnel costs as well as overall-factory costs per 1 ton of output, heating of scrap is usually economically profitable, if a satisfactory technical solution has been found for the problems related to scrap heating. In order to get the right idea of possible effectiveness of scrap preheating,

Y.N. Toulouevski, I.Y. Zinurov, *Innovation in Electric Arc Furnaces*,
DOI 10.1007/978-3-642-03802-0_6, © Springer-Verlag Berlin Heidelberg 2010

it is necessary to quantitatively estimate all three components of the useful energy of the heat E_{MET}.

6.2 Consumptions of Useful Heat for Scrap Heating, Scrap Melting, and Heating of the Melt

At tapping temperatures 1620–1640°C the value of E_{MET} is approximately equal to 390 kWh/ton. This useful heat is accumulated during the heat at the stages of scrap heating, scrap melting, and heating of liquid metal to tapping temperature. The heat capacities of solid and liquid iron and its melting heat are such that the energy needed for heating of scrap to the melting point of 1530–1540°C is approximately 294 kWh/ton, that of for melting is 75 kWh/ton, and only about 25 kWh/ton is needed for heating of melt from the melting point to the tapping temperature, Table 6.1.

Thus, three-fourths of all the useful heat are used for heating of scrap to the melting point, and only one-fourth for the melting of scrap and heating of liquid metal. As scrap heating requires the highest energy consumptions, the productivity and effectiveness of EAFs depend to the greatest extent on methodology and energy efficiency of this process. If the abovementioned processes went on sequentially, for instance, in three different baths, then in the last bath only 5–6% of total useful heat

Table 6.1 Heat capacity *c* and enthalpy *E* of solid and liquid iron

t, °C	*c*, Wh/kg × °C	*E*, kWh/ton	*t*, °C	*c*, Wh/kg/kg°C	*E*, kWh/ton
25	0.124	3.1	900	190	170.7
50		6.5	950		181.0
100	0.130	13.0	1000	0.190	189.7
150		19.8	1050		198.4
200	0.134	26.8	1100	0.188	206.9
250		34.1	1150		215.9
300	0.139	41.6	1200	0.187	224.8
350		49.5	1250		233.9
400	0.144	57.7	1300	0.187	242.9
450		66.5	1350		254.4
500	0.151	77.5	1400	0.190	265.9
550		85.0	1450		275.1
600	0.159	95.1	1500	–	286.7
650		106.1	1536 solid		294.2
700	0.169	118.7	1536 liquid	–	369.5
750		131.7	1600		384.0
800	0.181	145.0	1650	0.23[a]	394.7
850		158.0	1700		405.6

Notes: The data can be used for low-carbon steels having enthalpies *E* higher by 3.6% at 100°C, 2.9% at 500°C, 1.5% at 1000°C, 1.8% at 1300°C.

[a] The average value of heat capacity in the range from 1550 to 1700°C, Chap. 4, Sect. 4.4.

would be used for heating of the liquid metal obtained after the melting of all the scrap.

However, in reality, in conventional EAF all these processes take place simultaneously. When lumps of scrap are heated by electric arcs, their partial or complete melting occurs. The melt formed flows down to the bottom of the furnace, the level of the liquid bath rises, and the substantial part of the scrap is immersed in the melt with the temperature much lower than the melting point. This is very typical, especially for the furnaces operating with a so-called hot heel which means that the substantial part of the liquid metal and slag from the previous heat is being left in the bottom after tapping and for the Consteel process as well.

Further heating and melting of the lumps of scrap occur in the liquid bath in which temperature grows due to intensive heat transfer from the external and internal sources of energy. The need for melting the significant masses of scrap after their immersion into the liquid bath makes this stage of the heat relatively time-consuming. On average it takes about 40% of power-on time. In order to shorten this stage, it is necessary to intensify the scrap heating to highest possible temperatures prior to immersion of scrap into the melt. This can be achieved by high-temperature preheating of scrap.

6.3 High-Temperature Heating of Scrap

6.3.1 Calculation of Potential of Electrical Energy Savings

In the rolling mills steel billets are heated by the burners in the furnaces to medium mass temperatures of 1150–1250°C. At 1250°C the enthalpy of iron is 234 kWh/ton, Table 6.1. If utilization of the burners made possible to heat scrap to the same temperature level, it would lead to a radical change and an improvement in power engineering of modern EAF.

The aforesaid can be explained by the approximate calculation utilizing data presented in Sects. 5.3, 5.4.1, and 5.4.2 in Chap. 5. Let us take a look at Eq. (5.4) in Chap. 5: $E^*_{\mathrm{EL}} + E^*_{\mathrm{NG}} + \sum E^*_{\mathrm{CH}} = E_{\mathrm{MET}}$. In this case, when the scrap is heated by burners to 1250°C, useful heat of natural gas is equal to the enthalpy of scrap at this temperature, $E^*_{\mathrm{NG}} = 234$ kWh/ton. It is known that $E^*_{\mathrm{MET}} = 390$ kWh/ton. Substituting these values into the equation gives $E^*_{\mathrm{EL}} + \sum E^*_{\mathrm{CH}} = 390–234 = 156$ kWh/ton. $\sum E^*_{\mathrm{CH}} = E_{\mathrm{CH.MET}} + E^*_{\mathrm{CH.COK}}$. In the modern EAFs heat released from oxidation of iron and its alloys $E_{\mathrm{CH.MET}}$ is approximately equal to 100 kWh/ton, Chap. 4, Table 4.1. This heat is completely absorbed by the bath. On the contrary, absorbing of chemical heat of coke is characterized by quite low values of the η coefficients. But even if we completely disregard the value of $E^*_{\mathrm{CH.COK}}$, from the expression $E^*_{\mathrm{EL}} + E_{\mathrm{CH.MET}} = 156$ kWh/ton we will be obtain $E^*_{\mathrm{EL}} = 156–100 = 56$ kWh/ton. Considering $\eta_{\mathrm{EL}} = 0.7$, electrical energy consumption in the case is $E^*_{\mathrm{EL}} = 56/0.7 = 80$ kWh/ton.

In the modern EAF operating without heating of scrap, electrical energy consumption can be assumed to be equal to 345 kWh/ton. Therefore, heating scrap to

1250°C could ensure reduction in electrical energy consumption E_{EL}, as a minimum, by 345–80 = 265 kWh/ton, or by 345/80 = 4.3 times. It might be assumed that natural gas with the calorific value of 9.5 kWh/m^3 is utilized for heating of scrap, and $\eta_{NC} = 0.6$. Then the consumption of natural gas V_{NG} required for heating of scrap to 1250°C (enthalpy is equal to 234 kWh/ton) is $V_{NG} = 234/9.5 \times 0.6 = 41$ m^3/ton.

6.3.2 Sample of Realization: Process BBC–Brusa

The calculation given above is not an abstract one. In principle, the technical capability and energy efficiency of the high-temperature heating of scrap were confirmed in the 1970s on an industrial scale using the installations which combined an EAF and a rotary tube-type heating furnace. One of the first installations of this kind was the steelmelting unit of BBC–Brusa (Italy) with a capacity of 36 ton equipped with a low-power transformer of 7.2 MW [1]. In this unit, a 13 m long rotary heating furnace (1) is installed above an EAF, Fig. 6.1. The gases escaping through an opening in the EAF roof are drawn into the tube-type furnace. The scrap is continuously charged into the bath of the furnace through the same opening. When passing through the tube furnace, the gases are heating the scrap coming from a batcher (2) equipped with vibrator (3). At the upper end of the furnace the cooled gases are drawn into a fume hood (4) and are removed for purification.

Gas burners (5) are located at the bottom of the rotary furnace. The scrap passes through the furnace for 6–10 min. During this time the scrap is heated up to medium mass temperature of $t_{SCR} = 1000$°C. This temperature was reached not quite due to off-gas heat but mostly due to the burners which account approximately 73% of

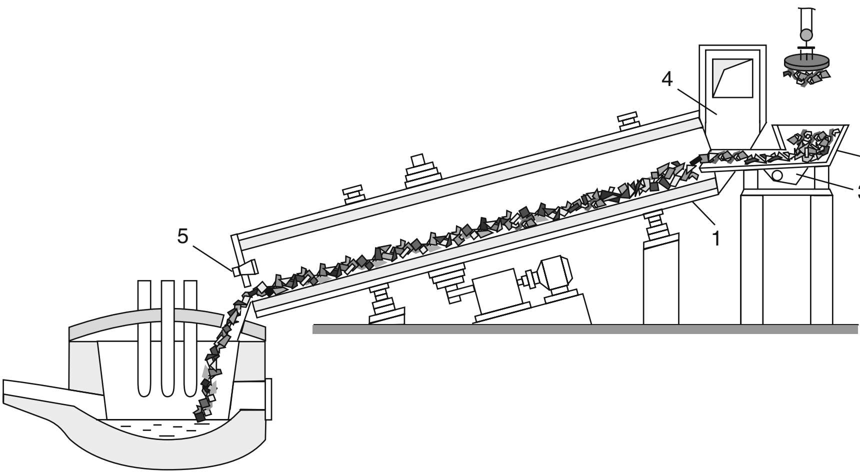

Fig. 6.1 Combined unit BBC–Brusa (designations are given in the text)

all heat coming into the rotary furnace. Rotation of the furnace prevents welding of the scrap lumps despite their high temperature and assures that heat from the refractory lining is being used for scrap heating. This enhances the advantages of countercurrent system of gas and scrap motion which makes gases exit the furnace at low temperature. The thermal efficiency of the rotary furnace calculated for the total heat input reached approximately 45%.

Performance of the BBC–Brusa unit for 3 years of service shows great potentialities and principle advantages of high-temperature scrap heating. Its performance indices correspond well to the calculation results given above. With natural gas consumption of 30 m^3/ton, electrical energy consumption was cut by 220 kWh/ton. Furnace productivity increased up to 100,000 ton per year which at that time was equal to the productivity of a furnace with the same capacity, but equipped with high-power transformer. Continuous charge of scrap assured very quiet burning of arcs and low noise level (less than 80 db). Durability of the refractory lining of the rotary furnace was 1500 heats.

Despite the advantages attributed to the high-temperature scrap heating, such units had quite limited use and only for a short period of time. This can be explained mostly by the fact that for the modern high-productivity EAF the dimensions of a rotary furnace required call for really too big size and height of the buildings for EAF shops. Besides, rotary furnaces can operate only using properly prepared fragmentized scrap. This narrows raw material supply base and increases cost. The units with rotary furnaces also have other significant drawbacks, which prevent them from being used in the modern steelmaking shops. Nevertheless, the impressive results obtained on BBC–Brusa units promoted a search for new options of high-temperature scrap heating.

6.4 Specifics of Furnace Scrap Hampering Its Heating

In EAF, as a rule, the cheapest light scrap is used. It has low bulk density of approximately 0.79–0.8 ton/m^3. 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 to 100–150 mm. Internal thermal resistance of such lumps is so low that each single lump can be preheated 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 the relatively large bales. The bales 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. The chips are produced in large amounts and require utilization. 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 (1000–1200°C) gas is used for preheating of scrap, pockets of burning, and melting of small fractions can be formed in the heated layer. When this occurs, the separate scrap lumps are welded together forming so called "bridges" which obstruct normal charging of preheated scrap into the furnace. Because of this preheating of metal chips is usually avoided.

In the temperature range 400–600°C oil and other organic materials contained in the scrap sublimate and burn releasing badly smelling toxic gases, which requires serious measures of protection of the atmosphere of a shop and as well as environmental protection. This problem is discussed in detail in Chap 14. At temperatures higher than 800–900°C the fine scrap is oxidized intensely due to its very large surface area. This decreases the yield and can create dangerous situations during charging scrap into the furnace. Charging of large quantities of fine strongly oxidized scrap into the liquid bath can cause an explosion-like release of CO. Thus, the specifics of the steel scrap utilized in EAF create certain difficulties for its preheating, especially for the high-temperature preheating.

6.5 Processes of Heating, Limiting Factors, Heat Transfer

6.5.1 Two Basic Methods of Heating

Many different methods and devices utilizing the fuel and the heat of off-gases were offered for scrap heating before the heat. But only some of them were realized in practice on an industrial scale. Despite the variety of designs, they all were based on one of the two principally different methods of heating: either heating of the whole scrap pile in a large-capacity container, or heating of a relatively thin layer of scrap on a conveyor.

The first method was used in the most common practice of charging scrap into the furnace by baskets, usually by two or three of them. In this method, baskets themselves were utilized as containers for the scrap being heated. Sometimes, the specially designed baskets or buckets were used as the containers for heating of scrap to higher temperatures. Such buckets were made of heat-resistant steel and were equipped with burners. These buckets were air- or water-cooled, as well.

Two different types of devices were used for the realization of the conveyor method of heating: belt conveyers of special design or sectional shaft preheaters. On a belt conveyor, the scrap moves toward the furnace in a horizontal direction, as in the Consteel process. A sectional shaft preheater is also a conveyor-type device installed vertically above the furnace. In a sectional shaft preheater, the scrap moves, due to gravity, from the upper sections into the lower ones.

6.5.2 Heating a Scrap Pile in a Large-Capacity Container

A device for this heating method is shown schematically in Fig. 6.2. The high-temperature gases come into an upper chamber (3) of container (1), installed in heating chamber (2). These can be either off-gases or gases obtained from combustion of fuel in the burners (4). A chamber (3) ensures uniform distribution of gases over a cross-section of a layer of scrap (5). Passing through the container charged with scrap from the top to the bottom, the gases heat the scrap, cool down, and leave container (1) through openings (6) in its lower part. The off-gases are removed through EAF evacuation system. The heated scrap is charged into the furnace through an opening bottom (7). For this purpose the container with the heated scrap is transported to the furnace and is placed above it.

The basic thermo-technical principles of heating the scrap in accordance with Fig. 6.2 can be discussed without carrying out quite complex calculations for this non-stationary process. Unlike that of separate lumps of scrap, thermal conductivity of a layer of lumps caused by the contact between the lumps both in vertical and horizontal directions is negligible and can be ignored in calculations. Therefore,

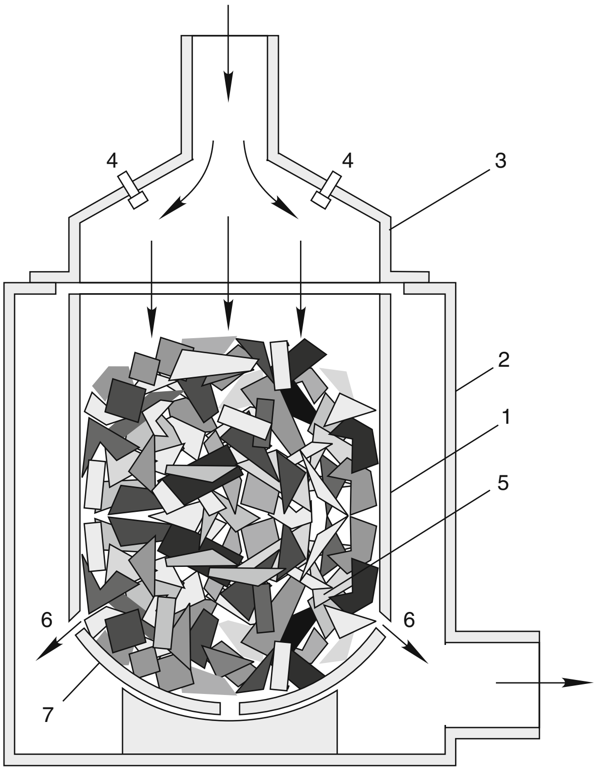

Fig. 6.2 Schematic diagram of scrap heating at charging basket (designations are given in the text)

the heat losses through the sidewalls of the container are also so small, that the container can be cooled by air and even by water without reducing the efficiency of scrap heating. The heat transfer by radiation from the heating gases can also be disregarded, since the gaps between the lumps are small and the emissivity of the gases in them is low.

The basic forms of heat transfer in the layer of scrap are convective heat transfer between the high-temperature gases and the surface of the lumps and heat radiation between the heated lumps. Radiation becomes essential when the lumps temperature is higher than 300–350°C. Because of the complete uncertainty in estimation of the free surface of scrap lumps contributing to the heat exchange, it is impossible, in this case, to separate these two forms of heat transfer. Therefore, in the approximate calculations of heat transfer intensity in the layer of scrap, as in the layer of other bulk materials, usually the so-called volumetric overall heat transfer coefficient, α_V, kW/m^3 $\times$ °C, is used. This coefficient considers both the convection and radiation, and is related not to the surface area unit, like α-coefficient, but to the volume unit of the layer, although this does not correspond to the process physics.

During the heating, medium mass temperature of the scrap increases from the initial near-ambient value to the finite value, t_{SCR}. In doing so, at any given moment of time the temperature of the upper layer t'_{SCR} is considerably higher than the temperature of the lower layer t''_{SCR}. The temperature of gases entering the scrap preheater t'_G can change within wide limits. To avoid overheating of the upper layer of scrap, this temperature is regulated by the dilution of gases with cold air. Usually t'_G does not exceed 800–1100°C. By controlling the degree of dilution, it is possible to keep t'_G at a relatively constant level or to change this temperature following a certain schedule both in the case of heating scrap only by off-gases and when utilizing additional fuel as well. The temperature of gases exiting the preheater t''_G gradually grows as the scrap heats up, but does not usually exceed 250–350°C at the end of the heating. All the variations of temperatures with both height of a layer and heating time have a nonlinear way, which considerably complicates the calculations. Because of a very large area of heat-absorbing surface of a scrap layer, this type of heating devices has high thermal efficiency. In such devices the heat efficiency coefficient of the gases η is usually equal to 0.6–0.7.

The maximum achievable medium mass temperature of the scrap $t_{SCR.max}$ heated in accordance with the scheme in Fig. 6.2 can be limited by three factors: the discussed above specifics of the scrap itself; the amount of heat in the gases available for heating as well as the heating time which strongly depends on the conditions of heat transfer from the gases to the scrap. Limitations due to the amount of heat available occur when the scrap is heated only by off-gases. It is not difficult to calculate the temperature of $t_{SCR.max}$ for this case.

The total enthalpy of off-gases includes both physical and chemical heat produced by post-combustion of CO and other combustible components in the off-gas evacuation system, in the modern EAF is equal on average approximately to 20–25% of the electrical energy consumption, i.e., about 80 kWh/ton. If $\eta = 0.7$, then $80 \times 0.7 = 56$ kWh/ton of useful heat can be transferred to the scrap. This value corresponds to the value of temperature $t_{SCR.max}$, which is close to 400°C, Table. 6.1. In practice, however, $t_{SCR.max}$ does not usually exceed 300–350°C due to the difficulties caused by the explained above specifics of scrap. Thus, the amount of heat in the off-gases allows heating the scrap only to relatively low temperatures.

The limitation discussed above can be overcome by utilizing in the scrap heating devices the additional energy of the fuel combusted in the burners. The scrap can also be heated by the burners only. This type of scrap heating devices has the advantage that they make possible the utilization local fuels which were not used before. The electrical steelmelting shops, which are the part of the integrated plants, can utilize coke gas or converter gas as such a fuel. However, in all cases the value of $t_{SCR.max}$ is limited by the process of heat transfer. This process is described by the equation:

$$q^* = \alpha_V(\bar{t_G} - t_{SCR}) \times \tau/\rho, \text{ kWh/ton}, \tag{6.1}$$

q^*– amount of useful heat transferred from gases to scrap, kWh/ton
α_V– volumetric heat transfer coefficient, $kW/m^3 \times °C$
$\bar{t_G}$– averaged over height of the layer as well as overheating time temperature of gases, °C
t_{SCR}– average mass temperature of scrap, °C
$t_G - t_{SCR}$ – average temperature difference Δt_{AVE}, °C
τ– heating time, h
ρ– bulk density of the scrap, ton/m^3

Time τ needed for heating the scrap in a large-capacity container to the average mass temperature of t_{SCR} can be calculated from Eq. (6.1):

$$\tau = \rho \times q^*/\alpha_V(\bar{t_G} - t_{SCR}). \tag{6.2}$$

The results of processing the published data on the values of t_{SCR}, Δt_{AVE}, τ, and ρ for heating of scrap in the baskets and buckets according to formula (6.2) showed that the α_V- coefficient for such devices is approximately 0.12–0.14 $kW/m^3 \times °C$ and a typical temperature difference $\Delta t_{AVE} = \bar{t_G} - t_{SCR}$ lies within the limits of 600–700 °C.

Substitution of these values into formula (6.2) allows to find the time of τ needed for heating of scrap to the medium mass temperature t_{SCR} when $\rho = 0.7$ ton/m^3. For $t_{SCR} = 500$ °C ($q^* = 77.5$ kWh/ton, Table. 6.1) $\tau = 0.64$ h (39 min), and for $t_{SCR} = 600$ °C ($q^* = 95.1$ kWh/ton) $\tau = 0.78$ h (47 min). Such scrap heating durations are incompatible with operation of the modern high power EAF in which the power-on time is substantially shorter than the τ-values calculated. Therefore, under the present-day conditions attainable temperatures of heating the scrap by the off-gases in accordance with the scheme in Fig. 6.2 are considerably lower than 500–600°C because of the insufficient intensity of the process of heat transfer only, not to mention the other limiting factors. This conclusion corresponds well to the data obtained in practice.

The possibilities of speeding up the scrap heating process in the large-capacity containers are quite limited. In order to shorten τ, the temperature difference Δt_{AVE} has to be increased through an increase in $\bar{t}_G$, formula (6.2). It is impossible to increase the temperature of gases at entry t'_G, because the overheating of the upper layer of the scrap is unacceptable. Therefore, $\bar{t}_G$ can be raised substantially only due to an increase in the exit temperature of gases t''_G. It can be achieved by increasing the fuel consumption in the burners and, at the same time, an amount of air, which dilutes the products of combustion. An increase in the amount of gases passing through the scrap with the same temperature t'_G will increase not only t''_G, but α_V as well. This, however, will sharply reduce the fuel efficiency coefficient η, which will considerably worsen the economy of heating.

6.5.3 Heating on Conveyor

Unlike heating in a large-capacity container, the scrap on the conveyor, in principle, can be heated to rather high temperatures and very quickly. This is explained by two advantages of heating on a conveyor: it allows, first, working with a relatively thin layer of scrap, and second, removing from a heating zone a portion of scrap as soon as it reaches the maximum temperature. This makes possible to avoid overheating of scrap without reducing the power of the source of thermal energy.

Heating of scrap on a conveyor on an industrial scale was implemented at the Consteel steelmelting units, Chap. 1, Sect. 1.4.3. However, contrary to expectations and initial advertising information, the high-temperature heating of scrap was not achieved at the Consteel conveyor. With the conveyors being approximately 30 m long, heating temperatures did not exceed those achieved by heating of scrap in the charging baskets. In the Consteel furnaces electrical energy consumption does not differ noticeably from that of the modern EAFs operating without preheating of scrap. For example, in the heat balance of a new 250-ton Consteel furnace, which is to be installed at the mini-mill under construction in Cremona (Italy), the enthalpy of the heated scrap is assumed to be equal to 18 kWh/ton. This corresponds to the expected temperature of approximately 150°C, Table 6.1, and comprises only 12% of an amount of heat of off-gases [2].

Such a low heat efficiency of off-gases is explained by ineffective scheme of heat transfer from gases to scrap in the Consteel process. In the tunnel, gases travel parallel to the surface of the scrap layer and do not penetrate deeply in the spaces between scrap lumps. The volume of gases is small in comparison with the cross-section of the tunnel. Therefore, the gas velocity, and, consequently, the intensity of the heat transfer from gases to scrap are considerably lower than in case of gases passing through the layer of scrap in a large-capacity container. As a result, generally only the uppermost thin layer of scrap is heated, whereas the overall thickness of the layer of scrap on the conveyor is quite substantial. For the 250-ton furnace this thickness is equal to 0.9 m [2]. The radiation from gases and tunnel lining also heats only the upper layer of scrap, because the topmost scrap lumps shield the lumps located lower. It is worth mentioning that, for the same reasons, the methods of scrap heating by off-gases similar in regard to heat-transfer conditions did not

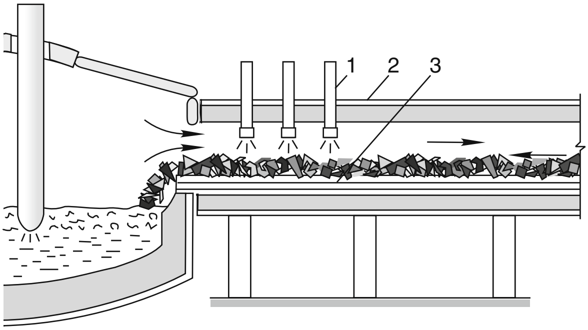

Fig. 6.3 Schematic diagram of scrap heating on Consteel conveyer by off-gases and burners (1 – oxy-gas burner; 2 – tunnel; 3 – special hot-resistant conveyer)

give satisfactory results in the so-called twin-shell EAF and earlier in the twin-shell open-hearth furnaces [3].

In order to realize high-temperature heating of scrap on a conveyor, it is necessary to use the high-power burners rather than the off-gases as the basic source of heat, as in the BBC–Brusa units, Sect. 6.3.2. In the Consteel process the burners should be installed in the roof of the tunnel close to the furnace, Fig. 6.3. The tunnel is divided into two zones. The first zone, next to the furnace, is the zone of high-temperature heating of scrap by burners. The second zone occupying the remaining larger part of the tunnel is designed for preheating of scrap by the heat of the off-gases exiting the first zone. Such a countercurrent heat transfer scheme, when the scrap moves toward the flow of gases, allows to utilize the heat of the gases in the most efficient way and to use the fundamental advantages of conveyor heating.

In the first zone the flames of roof burners possessing high kinetic energy hit the surface of scrap at a right angle. The gases heated to the high temperature pass through the layer of scrap, spread over the surface of conveyor, and surround the lumps of scrap again when returning to the tunnel. Such aerodynamic conditions of gas flows ensure intensive heat transfer from the gases to the scrap as well as a fast and relatively uniform heating of scrap.

The effectiveness of this scrap heating method is proved by the experience accumulated in the converter steelmaking. In the past preheating of scrap in the converters by the high power oxy-gas or oxy-oil burners before charging the liquid iron was quite widely used. The burners were installed next to the oxygen tuyeres and lowered inside the converter cavity for the period of scrap heating. The power of the burners was usually 160–180 MW. Such burners could heat 100 ton of scrap to medium mass temperature of 700°C in approximately 7 min and efficiency coefficient of fuel in the burners was $\eta_B = 0.5–0.6$. It was established that for the given conditions the medium mass temperature of the heated scrap was not to exceed 800°C. At higher temperatures the heating economy drops sharply.

Data shown above allow calculating the power of burners needed for the high-temperature conveyor heating of scrap in the Consteel process. The initial data used for the calculation are scrap charging capacity of EAF – 125 ton; duration of scrap charging into the liquid bath $\tau = 0.5$ h; finite medium mass temperature of scrap preheated by burners – 800°C; temperature of scrap preheating by off-gases in the second zone of the tunnel – 200°C; coefficient $\eta_B = 0.6$.

Calculation. The enthalpy of scrap at 800°C is 145 kWh/ton, and at 200°C it amounts to 27 kWh/ton, Table 6.1. Due to the burners' operation the enthalpy of scrap grows by 145–27= 118 kWh/ton, or for the mass of scrap equal to 125 ton, by $118 \times 125 = 14{,}750$ kWh. This is an amount of useful heat obtained by scrap from the burners. An amount of thermal energy used by the burners is considerably higher and for $\eta_B = 0.6$ is equal to $14{,}750/0.6 = 24{,}583$ kWh. The burner operation time $\tau = 0.5$ h. Thus, the power of burners required is $P = 24{,}583/0.5 \times 10^3 = 49.2$ MW. If 4 burners are used, then the power of each burner should be 12.3 MW.

If the scrap is heated up to 800°C and the η_{EL}-coefficient is 0.7, Chap. 5, Sect. 5.4.1, then the electrical energy consumption will be reduced by $145/0.7 = 207$ kWh/ton, approximately to the level of 140 kWh/ton. Such a reduction of the electrical energy consumption would indicate a fundamental improvement in all the power engineering of the Consteel furnaces. But the major advantage of this heating method would be that the duration of melting of scrap preheated to high temperatures in a liquid bath is substantially shorter, and, consequently, the process productivity increases.

The main obstacle for achieving such results is insufficient durability of the special Consteel conveyors. Increasing durability to a required level presents formidable difficulties. Considering this problem, it makes sense to examine as an alternative design solution, an option of the high-temperature heating of scrap by off-gases and by burners in a sectional shaft preheater, which is, in fact, a special type of conveyor.

The schematic diagram of a sectional shaft preheater is shown in Fig. 6.4. The shaft of a heater (1) is divided into three or four chambers by the grids formed by the mobile water-cooled bars ("the fingers") (2). In each chamber there is a portion of scrap forming a relatively thin layer. The total mass of scrap in all the chambers is equivalent to the amount of scrap needed for one heat. Gases pass upward through all the chambers charged with scrap. The burners are installed under the lower chamber. They introduce the additional amount of heat required for the high-temperature heating of the whole amount of scrap. When the fingers of any of the grids split apart, the scrap drops onto the grid of a chamber located below.

When each new heat starts, all the scrap heated during the previous heat is already in the preheater. The scrap in the lower chamber is preheated to the maximum required temperature, whereas in the upper chambers the temperature is decreasing. The scrap in the top chamber has the lowest temperature. The heat starts with discharging scrap from the lower chamber into the furnace. Then the scrap is transferred, in order, from each chamber into the next chamber below. The scrap transferred into the lowest chamber is being further heated there during a certain short period of time, while the empty uppermost chamber is being charged with the cold scrap. As soon as the scrap in the lower chamber is preheated to the maximum required temperature, it is discharged into the furnace, and the next cycle of the scrap transfers from the top to the bottom and charging of upper chamber with a new portion of scrap is repeated. The total required for a heat amount of scrap

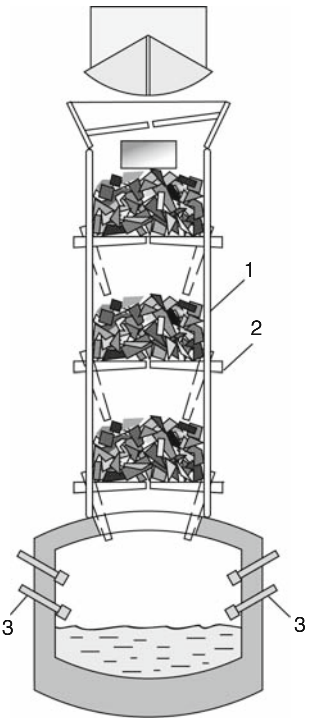

Fig. 6.4 Sectional shaft scrap preheater on EOF furnace (1 – shaft; 2 – finger; 3 – oxy-fuel tuyeres)

preheated to the maximum required temperature is charged into the furnace in three or four cycles, depending on the number of chambers. Concurrently with finishing of charging the scrap into the furnace, the preheater is filled with scrap for the next heat.

Preheaters like this successfully operated in the so-called energy optimized furnaces (EOF), which processed the charge containing 40–50% of scrap and 50–60% of hot metal. Due to preheating of scrap to the temperatures of the order of 850°C, the fuel consumption of these furnaces was low (about 10 kg/ton). Oxygen consumption, mostly for the bath blowing, was 60–80 m^3/ton. In the 1990s there were about 10 EOF furnaces in the world: in Brazil, India, Italy, and others countries [3].

Sectional shaft preheaters are very tall. Therefore, their installation in the electrical steelmelting shops is problematic and has not been implemented. However, the experience gained from utilizing such preheaters in the EOF has been used in designing the shaft-type electric arc furnaces.

6.6 Devices for Heating of Scrap: Examples

6.6.1 Heating in Charging Baskets

Due to its seeming simplicity, this method was one of the first quite widely used scrap heating methods. It has all the thermo-technical characteristics of heating scrap in the large-capacity containers. Mainly the off-gases were used for heating, and the idea to utilize off-gases as the free-energy source seemed especially attractive. Autonomous units equipped with gas burners were used in the relatively rare cases. Such a unit operated at the Electrostal plant in the 1970s. This unit was utilized for preheating of scrap before the heat in 20-ton EAFs producing mainly high-alloy steels.

The unit consisted of two identical chambers. The scrap in a charging basket with a capacity of 10–11 ton was heated in each chamber. The basket made of stainless steel was installed in the chamber with a flap cover with air–gas burners built in it. The burners were designed for natural gas combustion, with the air consumption coefficient close to one, followed by diluting combustion products with cold air. This allowed regulating the temperature of gases entering the basket within a range from 800 to 1150°C.

If the specific consumption of natural gas was 10–11 m^3/ton and heating time was 1.5 h, the medium mass temperature of heated scrap was in a range of 500–550°C, and the efficiency coefficient of gas η_{NG} was approximately 0.7. Scrap preheating reduced tap-to-tap time by 9–10% and the electrical energy consumption of the furnace by 72–78 kWh/ton. Taking into account the electrical energy consumption of the scrap heating unit itself (approximately 12 kWh/ton), overall reduction of the electrical energy consumption was 60–66 kWh/ton. The plant of Elektrostal used clean scrap only. Therefore, there was no problem of environment protection from toxic substances from the combustion of scrap contaminants.

In the 1980s, in a number of countries of Europe, Asia, and United States, the units for heating scrap by off-gases in the charging baskets became widespread on the furnaces with a capacity of from 25 to 150 ton. At that time more than 30 of such units operated in Japan alone. Usually, the regular charging baskets were utilized. The temperature of gases at the unit entry was about 1000°C, and at the exit it was about 200–300°C. The medium mass temperature of heated scrap did not exceed 300–350°C. Because of the low productivity of these units, usually only a part of the scrap was heated, for instance, two baskets out of three. Utilization of these units ensured reduction of the electrical energy consumption by 30–40 kWh/ton. Tap-to-tap time was shortened by 7–9%.

Two methods of heating scrap by the off-gases were used: with or without recirculation of gases. As per without recirculation method, the off-gases flow is directed into a basket with scrap placed in heating chamber, as shown in Fig. 6.2. Passing through a layer of scrap in a basket from the top to the bottom, the gases leave the basket through the openings in its lower part and get into the chamber. Then the gases are drawn off from the chamber by an exhauster and directed for cleaning.

However, very soon it became clear that such simple schemes were suitable for heating of sufficiently clean scrap only. As has already been mentioned in Sect. 6.4 of this chapter, the scrap usually contains relatively large amounts of oil, plastics, and other flammable materials. When being heated, these materials sublimate and burn, producing toxic gaseous chemical compounds. In order to avoid the emission of toxic gases into the atmosphere of a shop and into the environment, two technical solutions were introduced. One of them was to sort out the dirty scrap and place

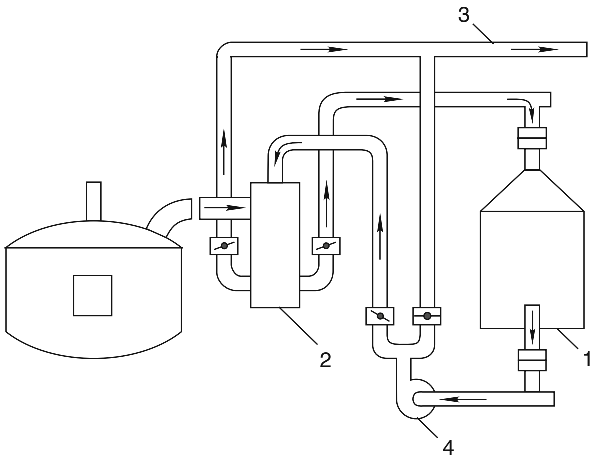

Fig. 6.5 Schematic diagram of scrap heating at charging basket with recirculation of gases (designations are given in the text)

it into a separate basket. Only the clean scrap was heated. Although preparation of scrap for the heat was complicated considerably, such units existed at some plants until recently.

The second solution was to use the units with recirculation of off-gases. Despite their lower effectiveness and higher energy consumption, these units became more widespread because of increasing environmental protection requirements. In the units with recirculation, Fig. 6.5, the cooled down gases after heating of the basket with scrap in chamber (1) return to a combustion chamber (2) installed in a duct of the direct off-gases evacuation from the furnace freeboard. In this chamber the gases are mixed up with the high-temperature gases extracted from the furnace and are additionally heated by burners. This leads to quite complete decomposition and burning-out of toxic emissions from the scrap. Approximately 60% of gases from the combustion chamber are returned to chamber (1) for scrap heating in the basket. The rest of gas is directed to a gas duct (3) for cleaning. Thus, with the help of an additional exhauster (4), the most of the gases exiting the furnace continuously circulates between the combustion chamber and the scrap heating device

It is necessary to have in mind that not only heating of scrap in the baskets, but transporting the baskets with the heated scrap to the furnace and charging hot baskets with fresh scrap as well cause air pollution both inside and outside of the shop. All these operations result in substantial emissions of smoke and toxic gases, which are practically impossible to capture. Therefore, considering an increased productivity of furnaces and, at the same time, more demanding requirements for environmental protection, the method of heating scrap in the charging baskets, being relatively low productive and insufficiently effective with regard to reduction of energy consumption, ceased to meet the current production requirements. Gradually, the application of this method has stopped everywhere. Subsequently, the persistent attempts to find other, more effective design solutions were undertaken.

6.6.2 DC Arc Furnace Danarc Plus

The basic requirements for heating of scrap by off-gases in the large-capacity container under the operation conditions of the modern highly productive furnaces with the short heat are to the greatest extent considered in the design of this 90-ton steelmelting unit developed by the Danieli Company (Italy) [4]. One of the most important features of the Danarc Plus furnace is tall furnace shell with a capacity sufficient for charging the entire amount of scrap needed for one heat (100 ton) in a single charge. There are 12 oxy-gas burners in the furnace shell installed in two rows one above another.

The scrap is heated in a special water-cooled bucket (1) with a capacity of 110 m^3, which, just like the furnace shell, can contain all 100 ton of scrap. The bucket is moved on a carriage (2) on rails located at each way from furnace (3), Fig. 6.6. The bucket can be placed in two positions: either above the furnace for discharging the heated scrap or aside the furnace. In the position aside the furnace the bucket is charged with fresh scrap with the help of standard fast opening baskets. During this operation, the off-gases are directed, using a special valve, through the bypass into the combustion chambers without passing through the bucket and then on cleaning. Thereupon the same valve changes the direction of flow, and the gases enter the bucket again to heat the scrap. Since the carriage with the bucket

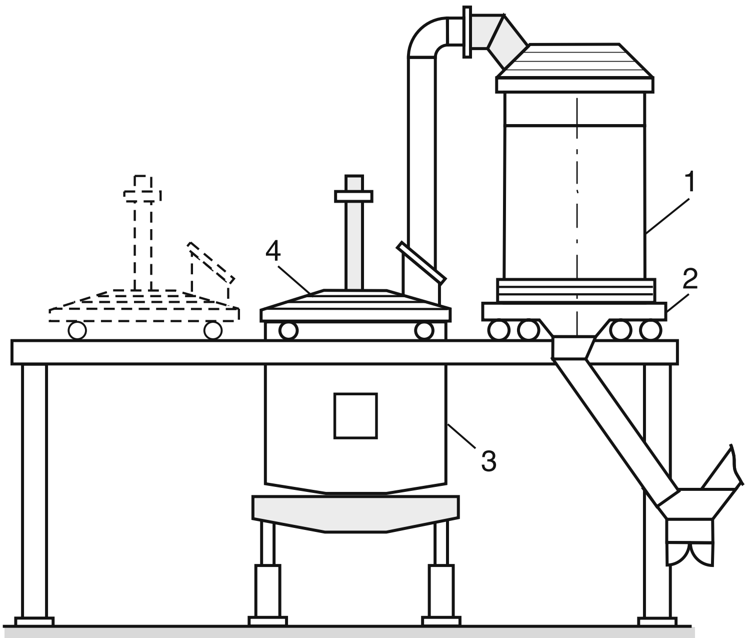

Fig. 6.6 Danarc Plus unit with scrap heating by off-gases (gas duct system providing for a bucket movement is not shown)

and another carriage with furnace roof (4) move simultaneously on the same rails, the duration of the entire operation of charging the furnace with scrap is less than 45 s, which considerably decreases unorganized emissions of gases and heat losses. All the unorganized emissions are captured by the hood located above the furnace under the roof of the shop.

The gases pass through the layer of scrap in a bucket from the top to the bottom. To increase the temperature of scrap heating, there are three air–gas burners with the power of 4.5 MW each installed in the upper part of the bucket. The temperature in the uppermost layer of scrap is maintained by these burners at the level of 1100–1200°C, while the temperature of the lowest layer is close to 200°C. According to the published data [4], the medium mass temperature of heated scrap t_{SCR} is 600–700°C.[1] The burners also ensure partial post-combustion of CO in the off-gases. The heat efficiency coefficient of all the gases passing through the scrap η is 0.55–0.65.

After heating the scrap in a bucket, the gases with a temperature of 300–400°C are directed into two combustion chambers placed in tandem. These chambers are equipped with the burners with the total power of 21 MW, which heat the gases up to 950°C. In combination with intensive stirring, high turbulence level of gas flows and their sufficiently stay long in the chambers, this ensures practically complete decomposition of toxic gases and post-combustion of CO.

In the Danarc Plus furnace the following results were obtained, Table 6.2, [5]. With scrap preheating, tap-to-tap time has shortened by 3 min, or by 7.1%, the productivity increased by 8.7%, and electrical energy consumption decreased by 21%. This confirms the significant impact of burners on scrap heating as well as the high heat energy efficiency of gases passing through the scrap.

In order to get quite a complete idea about energy efficiency of this steelmelting unit, it is necessary to analyze its heat balance for the zone, which includes both the furnace with the bucket and the combustion chambers of off-gases. Although the published data are insufficient for the heat balance completion, nevertheless they allow drawing some important conclusions.

The temperature of the gases at outlet of chambers is about 950°C, which is close to the temperature of the gases at the entry into the bucket. This means that, in order

Table 6.2 Some performances of Danarc Plus furnace operation [4]

Performances	With scrap heating	Without scrap heating
Electrical energy consumption, kWh/ton	260	330
Oxygen flow rate, m^3/ton	35	41.6
Tap-to-tap time, min	39	42
Liquid steel weight, ton	90	90
Productivity, ton/h	138	127

[1] These figures seem somewhat overstated.

to satisfy the environmental protection requirements, the amount of heat equal to approximately two-thirds of the total heat of off-gases used for scrap heating had to be brought back to the process. This is implemented due to heating the gases by the burners in combustion chambers. Thus, a complex and expensive heating system becomes inefficient. Furthermore, during the operation reliability of a number of the basic units of this system was found to be not quite sufficient. As a result, the Danarc Plus furnace was switched mainly to the mode of operation without scrap preheating. Nevertheless, the experience gained from development of this steelmelting unit is of a great interest. This experience should be considered when selecting the optimal direction for energy saving in electrical steel production.

6.6.3 Shaft Furnaces

As has been already mentioned in Sect. 6.5.3, the successful application of sectional shaft preheaters of scrap in the EOF stimulated the development of similar devices for EAF as well. The development of this direction is associated with the Fuchs Systemtechnik Company(Germany) and with the name of G. Fuchs. In the first furnaces built by this company the water-cooled shafts did not have fingers holding the scrap. 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 metal charge.

Later G. Fuchs has developed and put into operation at several plants the furnaces with one row of fingers in the lower part of a shaft, Fig. 6.7. The scrap is charged into the furnace by two baskets. At the tapping the scrap in 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 settles down and the shaft clears. The fingers are then shut, and the first basket of scrap for the following heat is charged on the fingers. By the tapping time this portion of scrap is already preheated by the off-gases to the maximum temperature.

With this heating method when gases pass through the scrap from the bottom to the top, the overheating and even the partial melting of the lower layer do not create any problems. The melt and the liquid slag formed flow down into the furnace and do not obstruct scrap discharging. This design concept allows to substantially increase the medium mass temperature of heated scrap. This is confirmed by reduction in electrical energy consumption in a finger shaft furnace to 285 kWh/ton. Another advantage of these furnaces is that a substantial part of the dust carried out from the

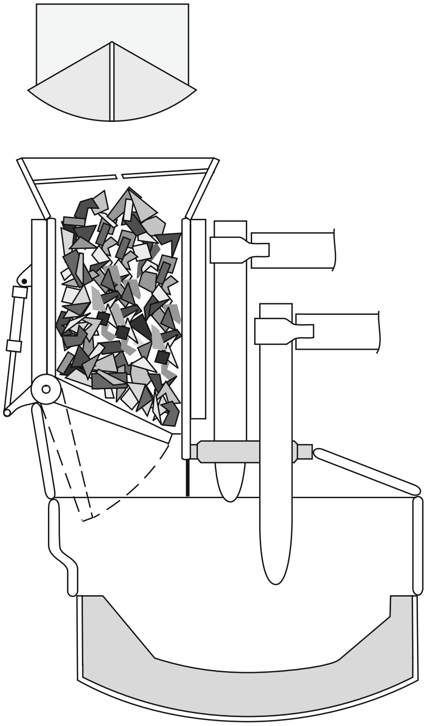

Fig. 6.7 Shaft furnace with holding scrap fingers (after tapping)

freeboard settles down in the layer of scrap filling the shaft. This increases the yield by approximately 1% [5].

The main problem for these shaft furnaces just like for the Danarc Plus furnaces is modern requirements of environmental protection. To meet these requirements, the furnace off-gases must be heated by the burners to high temperatures. This, to a considerable extent, negates the advantages of the reviewed furnaces associated with low energy consumption. In the furnaces of the new generation the shaft preheating of scrap at present is not considered, Chap. 1, Sect. 1.4.2.

6.6.4 Twin-Shell Steelmelting Units

These units are the complex consisting of two furnaces placed next to each other with common furnace transformer connected by a secondary electrical circuit with a rotary system current conducting arms and with electrodes. This system allows to place electrodes alternately in each of the baths. Several similar units 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. There were also twin-shell units built with scrap shaft heaters with no fingers. As in the usual shaft furnaces, these preheaters were located above each of the baths. The scrap was charged and the off-gases evacuated through these preheaters. Both baths of the twin-shell units were equipped with oxy-gas burners for heating of scrap and with devices for oxygen and carbon injection.

Technological operations in the twin-shell units are carried out in a certain order. For simplicity sake, one might discuss, as an optimal version, the operation of units with single scrap charging. Charging by several baskets does not change the principle of their operation, but it increases tap-to-tap time and decreases productivity. While in the first bath the electric arcs melt down scrap and heat liquid metal to the tapping temperature (operations with total duration of τ_1), in the second bath the other operations not requiring the use of electric arcs are carried out, namely the operations of tapping, closing a tap hole, preparing the furnace for the heat, scrap charging, and scrap preheating by burners. The total duration of these power-off operations is τ_2.

As soon as in the first bath the temperature of metal and the carbon content reach the required final values, the electrodes are moved to the second bath. The tapping is begun in the first bath, and the melting by the arcs of the preheated scrap in the second. Then the same operations are repeated in that same order. Since the tapping from the both baths has to follow in the identical time intervals, the operation of a twin-shell unit must satisfy the condition: $\tau_1 = \tau_2$. Tap-to-tap time for both baths τ_1 is defined by basic parameters such as electric arc power and oxygen consumption. Maintaining the total duration of all power-off operations at the level of τ_1 is easily achieved by controlling the scrap heating time.

The possibilities of a modern 120-ton twin-shell unit with respect to scrap preheating by burners are examined below. Having in mind the best performances of the EAF new generation, let us assume for a twin-shell unit $\tau_1 = 30$ min and the total duration of all power-off operations except of the operation of scrap heating equal to 8 min. Then possible maximum duration of scrap heating by burners is 30–8 = 22 min.

Let us determine the medium mass temperature of the scrap being heated for 22 min by the conventional sidewall oxy-gas burners. With the number of burners equal to 8 and the power of each burner equal to 3.5 MW, their total power amounts to 28 MW. The maximum efficiency coefficient of utilization of natural gas in the burners η_{NG} does not exceed 0.6, Chap. 5, Sect. 5.4.2. Assuming $\eta_{NG} = 0.6$, the enthalpy E_{SCR} for 130 ton of scrap preheated by burners is found: $E_{SCR} = 28{,}000 \times 22 \times 0.6/60 \times 130 = 47.4$ kWh/ton. The medium mass temperature of scrap corresponding to this value of enthalpy is close to 350°C, Table 6.1. Calculations using the actual data on natural gas consumption in twin-shell units give the same results.

When scrap is charged into the twin-shell unit by two or three baskets, only the first basket is charged into the second bath. It is impossible to settle down the charged scrap fast enough for creating the space for the second basket of scrap. Therefore, the first bath is charged with the cold scrap from the second and subsequent baskets. Such scrap preheating does not considerably reduce electrical energy consumption in comparison with the modern single-shell EAF, especially due to the fact that the heat losses with water and to the environment in the twin-shell units are approximately twice higher. This is confirmed by actual data. The electrical energy consumption of the operating twin-shell units equipped with burners is about 350 kWh/ton, and that of the shaft twin-shell furnaces with the natural gas consumption in the burners of about 11 m^3/ton is approximately 320 kWh/ton.

In principle, twin-shell steelmelting units have two potential advantages in comparison with the conventional furnaces. First, tap-to-tap time τ_1, provided that other conditions being equal (identical charge, capacity, electrical power, natural gas and oxygen consumptions, etc.), is automatically reduced approximately by 25% due to conducting of power-off operations in the second bath. Output per hour grows respectively. Second, the high-temperature heating of scrap by burners in the second bath becomes feasible, since the limitations typical for all other methods of high-temperature heating do not exist in this case. Only the combination of these advantages can justify the construction of twin-shell units, which require high capital costs, are more difficult to operate and occupy more space.

For the high-temperature heating of scrap charged in a single charge it is necessary to sharply increase the power and efficiency of the burners. Since this has not been done, the fundamental advantages of this type of heating in the twin-shell furnaces have not been realized. Two separate furnaces can ensure considerably greater productivity than one twin-shell unit. As a result, the options of reconstructing the existing twin-shell units into two independently operating furnaces with the separate transformers are being considered. Such reconstruction has already been carried out and has led to a considerable increase in the productivity of a shop [6].

The twin-shell units give most promising opportunities for the high-temperature preheating of scrap by the burners. However, these opportunities have not been realized yet. Does that mean that such heating capable of major increasing of energy effectiveness and productivity of the modern EAF is not achievable at all? The following chapter is dedicated to an analysis of this problem.

References

1. Neumann F, Leu H, Brusa U, BBC–Brusa is a steelmaking process, Stahl und Eisen, 1975, 95, No 1, 16–23
2. Arvedi G, Manini L, Bianchi A et.al. Acciaieria Arvedi: A new Giant Consteel in Europe, AISTech Conference, Pittsburgh, May 2008
3. Kudrin V A, Theory and technology of steelmaking, Moscow, Mir, 2003
4. Sanz A, Lavaroni G, Advanced approaches to electric arc furnace offgas management, MPT International, No 4, 72–82
5. Manfred X, Fuchs G, Auer W, Electric arc furnace technology beyond the year 2000, MPT International, 1999, No 1, 56–63
6. Dry R J, High productivity of EAF steelmelting shop, Iron & Steelmaker, July 2003, 23–27