Energy-saving DC twin shell arc furnace for melting low-grade scrap

With its energy optimized DC twin shell furnace, ABB offers steelmakers a melting unit that makes the production of raw steel from very low-grade scrap competitive in the marketplace. A sophisticated arrangement of burners and oxygen injectors ensures systematic preheating of the scrap for a considerable saving in energy and reduced environmental impact.

The development of the new energy optimized DC twin shell furnace, which is based on ABB’s proven DC EAF technology, centered on finding methods of optimizing total energy demand during steel production in order to reduce the electrical energy consumption. It was assumed that the main charge material would be low-grade scrap (ie, scrap with a low density and/or large amounts of organic impurities), to which smaller amounts of sponge iron, pig iron and similar would be added.

Combustion of the fossil fuel and natural residuals contained in pig iron and sponge iron is considerably better with the new energy optimized twin shell furnace than with conventional electric furnaces. This is due to the fact that the post-combustion takes place in the furnace itself and can be controlled precisely.

Table 1 gives some details underlining the performance of the new twin DC arc furnace.

### Energy balance of arc furnaces

#### ‘Outgoing items’ in the energy balance

The energy balance of an electric arc furnace, like that of every other kind of melting unit, has three main ‘outgoing items’:

- The molten charge
- Non-steady-state losses
- Steady-state losses

#### Molten charge

The yield, of iron as well as of wanted and unwanted elements that accompany it, fluctuates according to the type of charge material used. Under normal arc furnace conditions it is always less than 100 %.

#### Non-steady-state losses

These are the losses that arise during the actual melting process and therefore vary as a function of time. They do not occur, or occur only to a small extent, when the furnace is standing idle. Non-steady-state losses are:

- Off-gas losses
- Heat lost with the slag
- Radiation losses during arcing
- Charging losses
- Electrical losses

The non-steady-state losses are dependent upon the process. Although they cannot be avoided completely, they can be reduced and even minimized by appropriate control of the process.

In the case of the off-gas and slag losses, the primary goal is to reduce the total volume of the gas and slag. The radiation losses are best reduced by shortening the arcing time.

The charging losses represent a combination of the off-gas losses and radiation losses and are of the order

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In the case of scrap, the weight of the charge can be calculated using the following formula:

\[
\text{Charge weight} = \frac{\text{Tapping weight}}{\text{Yield}} \quad (1)
\]

Hence, for a tapping weight of 100 t and a yield of 92 %, charge material weighing 109 t will be needed.

To heat steel scrap of normal composition at room temperature to a tapping temperature of approximately 1,630°C, about 380 kWh is required per tonne of charge material.

\[
\text{Melting energy} = 380 \text{ kWh} \cdot 109 = 41,420 \text{ kWh} \quad (2)
\]

The melting energy is equivalent to the energy that is required physically, and consequently to the minimum energy demand.
of about 12–20 kWh/m² · min, referred to the surface area of the melt and the time between the roof being lifted and being closed again. For a furnace with a capacity of 100 t, these losses are approximately 400–450 kWh/min. The simplest way to reduce them is to reduce the charging time to a minimum.

Since the off-gases not only represent losses but also supply heat during their formation, it makes good sense to utilize as much of the perceptible and the chemically bonded energy as is possible in the melting unit itself.

The electrical losses in the transformer, rectifier, reactor and power supply components are mainly dependent on the value of the current and on the operating time. Like the radiation losses, they are best reduced by shortening the arcing time.

Steady-state losses
The steady-state losses are the losses that occur over longer periods of time and which for the most part lie outside of the range of the process control. They include:
• The heat lost via the furnace’s refractory lining.
• The cooling losses, i.e., the heat dissipated by the water-cooled wall and roof panels. These are also the main losses of the steady-state type.
The steady-state losses occur whether the furnace is being operated or stands idle. An idle furnace therefore represents a special cost burden to operators since the energy that is lost has to be made up for later.

A simple calculation helps to clarify this. A furnace of conventional design with a tapping weight of 100 t has water-cooled side panels with a total surface area of approximately 50 m$^2$ and a water-cooled roof about 30 m$^2$ in size. Each square meter of panel has to be supplied with 150 liters of water per minute. Assuming a difference of 5°C between the inlet and outlet cooling-water temperatures, the cooling losses will be in the order of:

\[
(50 + 30) \text{m}^2 \cdot 150 \text{ l/m}^2 \text{ min} \cdot \frac{1}{3} \text{ kcal/l} = 60,000 \text{ kcal/min} = 70 \text{ kWh/min} \quad (3)
\]

The total steady-state losses, including the hearth losses, of such a furnace then run to approximately 80 kWh/min. 80 kWh is enough to heat one tonne of cold scrap to almost 600°C.

### Table 1: Main data of the energy optimized DC twin shell electric arc furnace

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual production</td>
<td>&gt;750,000 t</td>
</tr>
<tr>
<td>Tapping weight</td>
<td>90 t</td>
</tr>
<tr>
<td>Electrical rating</td>
<td>64 MW</td>
</tr>
<tr>
<td>Transformer rating</td>
<td>100 MVA</td>
</tr>
<tr>
<td>Electrode diameter</td>
<td>28 inches</td>
</tr>
<tr>
<td>Electrode consumption</td>
<td>1.4 kg/t</td>
</tr>
<tr>
<td>Consumption of:</td>
<td></td>
</tr>
<tr>
<td>- coal</td>
<td>45 kg/t</td>
</tr>
<tr>
<td>- lime</td>
<td>50 kg/t</td>
</tr>
<tr>
<td>- oil</td>
<td>10 l/t</td>
</tr>
<tr>
<td>- oxygen</td>
<td>60 Nm$^3$/t</td>
</tr>
<tr>
<td>- electrical energy</td>
<td>&lt; 340 kWh/t</td>
</tr>
</tbody>
</table>

### Operating diagram of an arc furnace

\[ P, \quad t \]

### Schematic operating diagram of an arc furnace

\[ P, \quad t \]

‘Revenues’ in the energy balance

An electric arc furnace’s energy input comes primarily from the conversion of electrical energy into thermal energy, which is released in the arc. Besides the electrical energy, there are several other energy carriers that contribute to the release of chemically bonded energy during operation of an arc furnace.

The chemical conversion processes that take place can be divided into two groups:

- Purely metallurgical processes
- Additional combustion processes

### Metallurgical processes

The metallurgical processes, some of which are extremely complex, are capable of releasing huge amounts of energy. The actual amount of energy depends on the charge materials and the desired tapping qualities. For example, during the refining of pig iron in the steelmaking process, energy sufficient to melt scrap weighing approximately one third of the pig iron’s own weight is released.

Although this energy contribution reduces the electrical energy demand, the chemical energy released during the metallurgical processes cannot be considered as a substitute for electrical energy as it is anyway released as a natural part of these processes.

### Additional combustion processes

A genuine substitution for electrical energy is achieved by introducing additional fossil energy carriers in combination with air/oxygen.

Modern steelmaking technology offers many different ways of doing this. Some of them are given below:

- Additional burners
- Oxygen or oxy-carbon lances
- Bottom nozzles
- Oxygen injectors
A look will be taken later at the systems that are relevant for the DC twin shell arc furnace.

Operating diagrams

The relationships between the operating modes of a furnace and the steady-state and non-steady-state losses that occur can be shown best with the help of a graph known as an ‘operating diagram’ 2. The various energy sources (eg, additional burners) are of less interest in such a graph.

Full power (100%) is usually reached after 1.4 minutes via two preliminary stages representing 27 and 53 percent of the total power. How long full-power operation can be maintained depends upon the quantity of the charge material. If the majority of the charge is scrap, operation at full power will continue until about 70 percent of the material is molten.

When all of the charge is practically molten, the applied power is reduced to 66 percent of the full power. As this corresponds to a reduction in the voltage, the length of the arc is reduced. This is necessary to protect the water-cooled side panels, which are now exposed to the radiation given off by the arc.

3 shows a schematic representation of 2. The time axis in 3 for full power has been considerably shortened. Only the overheat phase (at 66 percent power input) is shown as a (small) true-to-scale block.

When the cycle time is 60 minutes, 15.5 of these will be idle time (eg, due to multiple charging) and tapping plus set-up time 4. The losses for a 100-t furnace under such conditions are given in Table 2.

During this type of operation, approximately 15.5 minutes of production time are lost during each cycle, causing a further loss of about 5,500 kWh. What is more, these losses have to be made up for during the operating time.

In fact, the losses lie at a much higher level, since for any given terminal rating several minutes are required to compensate for the losses. During these minutes, non-steady-state losses also occur, and these have to be compensated for during the same period of time.

Better utilization of the available energy is possible with a twin shell furnace in which each shell is alternately supplied with energy from the same electrical source 5.

If the cycle used is the same as in 4, the situation will be as follows:

- The cycle time is reduced from 60 to 54.5 minutes due to the times when the unit stands idle being shifted to the non-producing furnace. As a result, production is increased to 111 percent.
- The losses increase to 152 percent due to one furnace not being operational.

It is not possible, however, to take the situation in 4 and relate it directly to 5. Instead, the total power has to be increased to compensate for the extra losses.

As a result of increasing the total power, the cycle time is shortened again, which once more reduces the steady-

![Operating diagram of a single furnace with 3 charging buckets](image)

**Table 2:**

<table>
<thead>
<tr>
<th>Type of loss</th>
<th>Duration min</th>
<th>Charging loss kWh</th>
<th>Steady-state loss kWh</th>
<th>Total loss kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st charge</td>
<td>3.5</td>
<td>1,400</td>
<td>280</td>
<td>1,680</td>
</tr>
<tr>
<td>2nd charge</td>
<td>3.5</td>
<td>1,400</td>
<td>280</td>
<td>1,680</td>
</tr>
<tr>
<td>3rd charge</td>
<td>3.5</td>
<td>1,400</td>
<td>280</td>
<td>1,680</td>
</tr>
<tr>
<td>Tapping</td>
<td>3</td>
<td>1,400</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Set-up</td>
<td>2</td>
<td></td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Σ</td>
<td>15.5</td>
<td>4,200</td>
<td>1,240</td>
<td>5,440</td>
</tr>
</tbody>
</table>
state losses in the non-producing furnace, etc. Iteration and appropriate adaptation of the total power results in an optimum cycle time for the example considered of 42–43 minutes plus an increase in production to 140 percent. However, the losses also rise at the same time and by the same order of magnitude.

Consequently, while this concept allows a considerable improvement in production, it does not allow a saving in total energy. What is more, the investment and operating costs are higher because of the second vessel.

Operating diagram of an energy optimized DC twin shell furnace

Minimization of energy demand plus increased productivity

General

A reduction in the total energy demand and in the consumption of electrical energy can be achieved with the help of some significant design modifications, by adopting advanced technologies and by changing the method of charging.

If the melting phase consists of a single block, single charging of the standby vessel will almost completely exclude idle time in the operating vessel. The only downtime is caused by the movement of the electrode from one vessel to the other.

Tapping, set-up and single charging all take place as usual in the non-arcing vessel.

Although not used for melting, the standby furnace has another function which is of decisive importance for the overall process: it preheats the scrap.

This results in two essential advantages over every other twin furnace:
• The losses that occur during the idle time are compensated for by the preheating.
• Preheated scrap exhibits a better melt-down behaviour and allows a drastic reduction in the electrical energy consumption, plus a shorter melt-down time.

Plant description

The first energy optimized DC twin shell furnace is due to begin operating in April 1997 in Malaysia. Each shell has an inner diameter of 6.1 m and a tapping capacity in the range of 85 to 95 t. The hot heel can therefore vary between 20 and 30 t. The lower part of each shell is of the same basic design as the lower vessel of a normal DC electric arc furnace with the same diameter.

The upper shell, on the other hand, reaches a height of 6.5 m above the plat-
The height of the upper shell, and the increase in total furnace volume that has resulted from it, permits a single charge of even the lowest-grade scrap with densities of around 0.6 t/m³. In addition to the saving in time and electrical energy, a significant increase in production is also gained from the presence of the organic impurities, which are normally unwanted in conventional furnace processes.

It goes without saying that liquid or solid pig iron and/or sponge iron can be used as a substitute for scrap. To ensure good preheating and a sufficient height for the scrap inside the furnace, however, not more than 30 to 35 percent of the total scrap weight should be replaced by other Fe carriers.

The water-cooled panels of the upper shell are split into two sections. This design feature allows on the one hand faster replacement of damaged parts, and on the other greater flexibility in operation, for example when the larger furnace volume cannot be justified for a change in the charge material.

The height of the upper shell results in an electrode stroke of 8.5 m. To avoid excessively high momentum, the electrode arm is made of aluminium and is self-supporting. The electrode mast itself is a very sturdy steel construction. Interlocks prevent furnace movements when the electrode is inside the vessel. As a result of these design measures, the high-shell furnace is just as reliable as a standard type.

Production optimization calls for some attention to be paid to the charging of the scrap. To prevent damage to the water-cooled side panels and the oxy-carbon lances during operation of the furnace, scrap weighing more than 0.7 t/m³ should be charged to a level no higher than the sill of the slagging door. For good results, around one third of the total amount of coal should be charged together with the heavier scrap pieces, plus one third of the total lime or dolomite. The rest of the additives are fed through a separate opening in the roof either continuously or in doses during the melting process.

The steel tapped from the melting furnace is further treated and heated in a ladle furnace with swivelling electrode mast. Two separate tracks run between the melting and the aftertreatment areas. This feature is a logical development of twin shell melting, and sim-
plifies the logistics of the overall steel-making process, ranging from the melting furnace to the continuous caster.

Charge materials
Alongside the other types of charge material, such as pig iron and sponge iron, scrap plays a key role in the design and operation of the DC twin shell furnace.

The furnace is unconventional in that it is designed to melt cheap, low-density scrap (less than 0.6 t/m³) containing relatively large amounts of organic impurities.

Both the low scrap density and/or organic impurities play an important role in achieving good preheating results. The absence of organic impurities can be compensated for by adding fossil fuels, such as car tyres.

Low-density scrap
The best preheating results are achieved with a high scrap surface to scrap volume ratio.

The preheating of the scrap follows four physical principles:
• Heat radiation
• Gas convection
• Heat exchange
• Heat conduction

The heat radiated by the flames, while highly efficient, is only of significance locally within the scrap pile.

The heat transfer due to convection of the hot combustion gases, although not as efficient as that due to the radiation, is not restricted locally. The efficiency of the heat transfer is influenced by the residence time of the gas (high scrap pile = long residence time) and the temperature gradient (cold scrap = high heat transfer).

Another factor besides the radiation intensity and the residence time of the gas (or temperature gradient between the gas and scrap), is the intensity of the heat exchange, which depends mainly on the surface area of the piece of scrap. The larger the surface area, the more thermal energy it will be able to absorb.

Comparison of a normal DC arc furnace (a) and an energy optimized furnace (b)

Comparison of the surfaces of two bodies of the same weight (m) and same volume (V) but with different dimensions (Ac)
per unit of time. shows how the surface areas of two bodies having different geometries but the same weight can vary.

Not only the heat exchange is strongly dependent on the geometry of the scrap; the geometry also has a strong influence on the heat conduction within the piece itself. It is seen that the distance from the side face to the center line of piece 2 is much shorter than for the piece with a square cross-section.

Organic impurities
Organic impurities are unwelcome in conventional arc furnaces since highly toxic substances, such as nitrogen oxides, furans or dioxins, can be formed at the high reaction temperatures. To reduce the level of these substances in the waste gas, complex and therefore costly gas-cooling and cleaning plant is necessary. For example, to eliminate or reduce dioxins, plant which can cool the off-gases at the rate of several 100 °C per second is required in the temperature range of 1200 to 500 °C.

Systematic scrap preheating allows the temperature profile in a (cold) scrap pile to be controlled in such a way that the formation of these unwanted toxic substances is avoided from the beginning. With the help of the new technology, the organic substances, which are otherwise unwanted, are utilized during the scrap preheat phase as valuable fuels.

The process
The heat cycle of a furnace is about 80 minutes, being split into two sub-processes lasting 40 minutes each:

- Sub-process 1: tapping, maintenance as necessary, charging (1 or 2 times), preheating
- Sub-process 2: electrical melting with support from the chemical combustion energy, foaming slag method

Sub-process 1: scrap preheating
The scrap is preheated such that an average temperature of 550 °C is reached in the charged material before arcing starts. This average temperature is equal to a heat content of about 70–80 kWh/t charged scrap.

Assuming the required supply of oxygen, the energy needed for preheating is provided through the combustion of fossil fuels and/or the organic impurities in the vessel. To this end, lances, burners and oxygen injectors are arranged on four separate levels above the furnace platform.

The lowest level, in the area of the slagging door, is heated by oxy-carbon lances which are controlled by a manipu-

Arrangement of the oxy-carbon lances (1), burners (2) and oxygen injectors (3) for preheating of the scrap

Tangentially arranged burners ensure good mixing of the off-gases, which are rich in CO, and the oxygen from the injectors.
lator. At the level above this (just above the refractory lining in the lower vessel) there are four low-power burners, and above these the oxygen injectors on two different levels. These, like the burners, direct low-speed jet streams of oxygen tangentially into the furnace.

The lances and burners heat the scrap directly in front of them and at the same time promote post-combustion by supplying the necessary carbon monoxide. The oxy-carbon lances further produce the so-called foaming slag. The heat transfer capability of the foaming slag vis-à-vis the cold scrap is considerably better than that of hot off-gas.

The tangential alignment of the burners and oxygen injectors ensures much better mixing of the co-rich off-gases with the oxygen jet streams from the injectors.

The post-combustion of the carbon monoxide generated by the lances and burners plays a complex but very significant role during the preheating phase:

- The enthalpy of the post-combustion reaction $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$ is higher than the enthalpy of the reaction $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}$.

- $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO} - 26.4 \text{ kcal/mol}$
- $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 - 67.6 \text{ kcal/mol}$
- $\text{C} + \text{O}_2 \rightarrow \text{CO}_2 - 94.0 \text{ kcal/mol}$

- The post-combustion increases the energy yield while reducing the energy consumption and exhaust gas volume, thereby increasing the overall efficiency.
- Post-combustion produces heat sources within the material being heated.
- Off-gas heat which is absorbed by the scrap no longer has to be dissipated to the surroundings; the same applies to the post-combustion heat, most of which, like the rest of the waste heat, is dissipated in conventional processes to the off-gas ducts by cooling water and thus indirectly pollutes the atmosphere.

To avoid (local) over-oxidation of the scrap due to the abundant supply of oxygen, either coal or coke has to be added to the charge as mentioned above, depending upon the actual organic impurities.

Sub-process 2: melting

The arcing phase does not differ greatly from normal DC electric arc furnace operation. For example, the burners support the melting process for about 10 to 12 minutes, whereas the oxy-carbon lances are in operation over practically the whole arcing phase.

Nevertheless, there are five significant features that underlie the benefits of the twin shell furnace and stress its improved operation:

- The post-combustion during the melting and superheating reduces the electrical energy consumption.
- Foaming slag is capable of a much better heat transfer to scrap than gases at the same temperature, due both to the better contact and the incomparably longer residence time.
- The foaming slag reduces the cooling losses in the water-cooled panels, thereby increasing their lifetime.
- Foaming slag exhibits a much better cooling effect; the arc burns under the slag with approximately half its length.
- Foaming slag protects the graphite electrode from oxidation, so that electrode consumption is sharply reduced.

Post-combustion also continues, depending on the produced amount of CO, during the melting phase, thereby producing additional combustion energy inside the furnace vessel.

As long as scrap is in the furnace, this heat will continue to benefit the charge material, although to a lessening degree: on the one hand the heat supplied by the hot gases to the increasingly hotter scrap decreases, on the other there is...
a simultaneous reduction in the total scrap volume due to the melting process.

When most of the scrap is molten, the additional energy from the post-combustion compensates for the losses caused by heat being given off to the surroundings by the non-heated slag surface (about 10 kWh/t steel).

The foaming slag, which until now has been produced mainly towards the end of the melting phase and during superheating, is produced already during the preheating phase.

The described effect of the better heat transfer from an emulsion to a solid (compared with a gas of the same temperature acting on a solid) increases exponentially with this method; this is because the preheating of the scrap causes the foaming slag to continue rising inside the scrap pile, thereby heating an increasing amount of scrap. Scrap with a low density (ie, with a larger surface to volume ratio) has a favourable influence on the heat transfer and thermal equalization.

Originally introduced to protect the water-cooled side and roof panels from arc radiation, the concept of the arc burning under the slag allows arcing to take place at the same power but with half the arc length. At the same time, the losses via the water-cooled panels are reduced.

Thus, the higher the slag foams at the beginning of the melting process, the earlier these effects are achieved. What is more, this mode of operation has the additional advantage that the electrode is withdrawn much earlier from the oxidating atmosphere, substantially reducing electrode consumption.

With this method of operation, tapping weights of 85 to 95 t can be achieved with cycle times of less than 40 minutes. This corresponds to an annual production of more than 900,000 t of liquid steel.

Combustion system control
Each furnace is equipped with one valve stand for the burner supply and one for the oxygen injectors. The supply to the lance manipulator is controlled by means of the oxygen pressure in a separate pipe.

The burners are controlled via the back-flow temperature of the cooling water, allowing each burner to be shut off separately, for example in the event of clogging. To ensure trouble-free operation of the burners under normal conditions, they have to be supplied with oxygen and fuel at very low rates even when they are not in operation.

The metering system for the combustion and post-combustion consists of a probe, a sampling pipe, a CO/CO\textsubscript{2}/O\textsubscript{2} analyzer and a control cubicle \cite{12, 13}.

The probe, in effect a sampling pipe with self-cleaning mechanism, is mounted at the beginning of the water-cooled off-gas duct. The pipe has to be positioned carefully so as to avoid infiltration of air into the gas stream. The hot off-gas in the sampling pipe is cooled and ducted to the analyzer, where the gas composition is analyzed for CO, CO\textsubscript{2} and O\textsubscript{2}. The results are transmitted to the control system, where they are converted into setpoints and retransmitted separately to the different valves.

A precondition here is that the furnace characteristic is determined after the additional burners have been installed, and the burners are calibrated accordingly.

With this innovative melting technology and its DC twin shell furnace, ABB offers steelmakers the possibility of economic production of raw steel from low-grade scrap. The first twin shell furnace of the type described is due to begin operating in April 1997 in Malaysia.

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