Chapter 2
Electric Arc Furnace as Thermoenergetical Unit

2.1 Thermal Performance of Furnace: Terminology and Designations

There are different forms of energy. Heat is one of them. Heat is a form of energy used to realize the furnace thermal performance in a steel melting process carried out at high temperatures. Therefore, the term "thermal performance of a furnace" has a rather profound meaning [1]. According to the energy conservation law, heat does not appear out of nothing and does not disappear. All other forms of energy can be transformed into heat, for instance, electrical or chemical energy, in strictly equivalent amounts.

During heating of any body, a certain quantity of heat transfers to it from the heat source. This process is called heat transfer. The heat assimilated by the body increases its internal energy. The body temperature thus rises. When cooling down, the body gives a part of its internal energy (in a form of heat) to objects surrounding it. Heat transfer processes proceed at a practically constant pressure in EAFs and in other furnaces. In all such cases a change in internal energy of the body is equivalent to a change in what is called enthalpy. This thermodynamic parameter is widely applied in thermo-technical calculations. Enthalpy, like other kinds of energy, can be measured in Joules (J) or in kW-hours (kWh). As a Joule is a very small quantity (3600 kJ = 1 kWh), energy unit of kWh will be used further in most cases.

While solving heat engineering problems, knowing absolute body enthalpy values is not necessary. It is sufficient to determine the enthalpy changes ΔE, which are calculated per 1 kg of substance or per 1 m^3 (for gases). In processes taking place at constant pressure, these changes are calculated by the following formula:

$$\Delta E = c_p x \, \Delta t \quad \text{kWh/kg (or kWh/m}^3\text{)}, \tag{2.1}$$

Δt – temperature change,°C

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c_P – mean heat capacity of the body at a constant pressure (for gases) within temperature range Δt, kWh/kg°C (or kWh/m^3°C)

Heat capacity c_P is measured by a quantity of heat transferred to a body with 1 kg mass or with 1 m^3 volume (for gases) to raise its temperature by 1°C. Correspondingly, we can distinguish between specific mass or volumetric heat capacities. Since only enthalpy differences are determined, they are counted off the initial temperature equal to 0°C according to formula (2.1). Mean heat capacity values presented in the tables correspond to temperature differences between 0°C and t°C.

So far we did not pay attention to the fact that the same mass of gases can occupy a different volume depending on their temperature and pressure. It should be made clear what specific gas volume is meant in the determination of heat capacity given above, formula (2.1). The same is also true for all the other values related per 1 m^3 of gas as well as for all data and results of calculations where gas volumes appear.

In order to avoid this uncertainty and have a chance of comparing various values to each other it is assumed to reduce gas volumes to standard conditions, namely to temperature of t = 0°C and pressure of 760 mmHg (1.01 bar). The standard volumes of gases are designated as m^3 (*s. t. p.*).

From the ideal gas laws any volumes could be reduced to the standard conditions. According to these laws at a constant pressure the volume of a gas increases in direct proportion with an increase in its absolute temperature T, which is measured in Kelvin's degrees, K. On Kelvin's scale, degrees K are counted out from the absolute temperature zero equal to −273°C on Celsius' scale. The values of temperature differences Δt are identical in both scales. Conversion from K to °C is determined by the following expression: T, K = t°C + 273. Thus, the water boiling point 100°C amounts to 373 K as well as 0°C = 273 K on Kelvin's scale.

At a constant temperature the volume of a gas decreases in direct proportion with an increase in its absolute pressure p_{ABS}, which is equal to the sum of excessive pressure of a gas p (from a manometer) and atmospheric pressure 1.01 bar: $p_{ABS} = p + 1.01$ bar. In regular calculations the atmospheric pressure might be assumed as 1.0 bar (10^5 Pascal, Pa).

To reduce a gas volume V, m^3 with a temperature of t°C > 0°C and pressure p bar > 0.0 bar (from a manometer) to standard volume V m^3 (*s. t. p.*), the volume V m^3 should be divided by the value of $(t + 273)/273$ and multiplied by the value of $(p + 1.0)/1.0$. For instance, if with t = 500°C and p = 3 bar (from a manometer), V = 300 m^3 then V m^3 (*s. t. p.*) = 300 × 4 × 273/(500 + 273) = 423.8 m^3 (*s. t. p.*).

Further, as well as in Chap. 1, volumes of gases are assumed to be given in m^3(*s. t. p.*) unless otherwise specified but designation of (*s. t. p.*) is left out.

It is necessary to note some specifics of designations of different kinds of energy accepted in this chapter as well as in the following ones. Enthalpy is usually designated as I in thermodynamics. In this book, a common designation E is accepted for enthalpy and other kinds of energy, which are added quite often. This simplifies both presentation and learning of this material. In sections dealing

exclusively with heat transfer processes, heat quantity is designated as Q, kWh and q, kWh/m^2.

Chemical energy of reactions of iron and other elements' oxidation and reduction plays a great part in thermal performance of EAFs. Oxidation reactions release heat and are called exothermic. Reduction reactions are accompanied by the absorption of heat; they are called endothermic. An amount of heat released or absorbed per unit of an element involved in a reaction is called thermal effect or enthalpy of chemical reaction; in thermodynamics it is usually designated as H. According to energy conservation law, thermal effect of exothermic reaction is equal to decrease in total enthalpy of the reactants. Therefore, by convention a minus sign is ascribed to it ($-H$). Respectively, a plus sign is ascribed to thermal effect of endothermic reaction ($+H$). It is rather convenient to measure enthalpies of chemical reactions in kWh per 1 kg of an element (e.g., iron Fe), or 1 m^3 of gas (e.g., oxygen O_2).

In modern steelmaking shops, the required steel qualitative characteristics are achieved in ladle furnaces and other units of secondary metallurgy. The EAF itself is designed purely for thermo-technical task, namely to melt the materials charged into the furnace and to heat the melt up to the tapping temperature. At the same time, carbon percentage in the melt is reduced to required final value. To solve this problem, it is necessary, first, to release (generate) certain amount of heat in the furnace by means of electric arcs, oxygen-fuel burners, and other energy sources; second, to transfer the heat to materials melted and to the liquid bath. Thus, heat generation and heat transfer are the basic processes determining the production and other basic parameters of modern EAFs. All this gives grounds to classify electric arc steel melting furnaces as thermoenergetical units.

2.2 External and Internal Sources of Thermal Energy: Useful Heat

All heat energy sources could be divided into two groups, namely the external and internal sources, depending on their position relative to the materials melted and to the liquid bath heated. The external sources include electric arcs (not completely immersed into slag), oxy-fuel burners, CO (carbon monoxide) post-combusted above the bath, and other sources. Only a portion of the heat generated by external sources can be transferred to the solid charge or to the liquid bath. This portion is useful heat. The rest of the released heat energy is inevitably lost in the process of heat transfer. The better the heat transfer process is organized, the lower the level of the heat loss, the greater the portion of the useful heat absorbed by the charge or the bath, and, consequently, the lower the consumption of electrical energy and fuel.

The internal energy sources include oxidation reactions of carbon, iron, silicon, and other elements contained in the melt. All these exothermic reactions release great amounts of heat. The heat generated in the bath itself is practically fully absorbed by the bath, because in this case the heat transfer process is not involved. Thus, almost all the heat generated by internal sources is useful.

In the course of the heat, the useful heat transferred to the solid charge and the liquid bath is accumulated in the melt and increases its enthalpy. At the same time, the temperature of the melt also rises. The final enthalpy of the bath just prior to tapping is equal to the sum of enthalpy of the metal at the tapping temperature E_{MET} and enthalpy of the slag E_{SL}. The value of enthalpy E_{MET} is equal to the quantity of useful heat accumulated by metal over the course of the heat. This quantity is called useful heat of the entire heat. It depends on the tapping temperature and is close to 400 kWh/ton of liquid steel.

If scrap and other metallic components of the charge, for instance, pig iron, are charged into the EAF in a cold state (at ambient temperatures), their enthalpy at the beginning of the heat can be disregarded. In that case, the enthalpy E_{MET} consists only of contributions of useful heat obtained from all the abovementioned external and internal energy sources. If preheated scrap or hot metal is charged into the furnace, then their enthalpy E_{SCR} contributes greatly to the useful heat of the heat E_{MET}. In that case, the share of all the external energy sources is reduced accordingly, as well as the specific consumption of electrical energy and fuel.

Sometimes, the enthalpy of final slag E_{SL} is also included into the useful heat of the heat. However, there is no substantial ground for that. The purpose of the heat is to produce metal, but not slag. The enthalpy of the slag tapped out of the furnace together with the metal is, in essence, lost heat, as well as that of the slag tapped out prior to metal tapping. Along with other heat losses, heat losses with the slag should be reduced as much as possible by reducing the amount of slag.

2.3 Factors Limiting the Power of External Sources

In order to shorten tap-to-tap time and to increase EAF productivity, it is necessary to increase the power of electric arcs, oxy-gas burners, and other external heat energy sources. Increasing the power of these sources in itself is not a problem. Thus, for instance, the power of a burner, used in oxygen converters for preheating scrap prior to charging of hot metal, is usually equal to 150–170 MW. The power of the burners used in EAFs is ten times lower than that of the converter burners. Usually it does not exceed 3.5 MW.

A similar situation is observed with regard to the EAF's transformers. Their power is much lower than that of the transformers used in electrical circuits. It is obvious that the problem consists not in the burners and the transformers themselves, but in eliminating the factors which limit the power of heat energy sources under specific conditions of electric arc furnaces. All these limiting factors could be divided into two fundamentally different groups, the first being the factors inherently connected with the physical–chemical processes taking place in the EAF, and the second being the external, sometimes random factors not connected with those processes directly. Let us identify, in brief, the first group as inherent factors and the second group as external factors. The vast group of external factors includes, for example, insufficient power of the external network supplying

electricity for the EAF, insufficient fume exhauster draught which restrains the carrying capacity of the furnace gas removal ducts, insufficient power of bag house, etc. The importance of these factors is quite obvious. Eliminating their restrictive effect is not connected with interference into physical–chemical processes of the heat and does not require improvement in carrying out of these processes. The problem is frequently reduced to the additional capital investments required for eliminating the bottlenecks such as replacement of fume exhausters or modernization of gas cleaning system.

The inherent limiting factors are inseparably linked to basic physical–chemical processes such as carbon oxidation during the oxygen blowing of the bath, stirring of the bath with carbon monoxide bubbles and oxygen jets, scrap iron oxidation by products of complete gas combustion in oxy-gas burners, and slag foaming. All these factors limit the reasonable power level of external heat energy sources as they strongly affect the heat transfer process conditions.

2.4 Key Role of Heat Transfer Processes

As a rule, it is the processes of heat transfer from a heat source to charge materials or the liquid bath that finally determine what part of energy generated in the source is converted into useful heat. If this portion of energy decreases substantially while the power of the source increases, then such an increase in heat generation becomes inexpedient. In such cases, it is necessary in the first place to improve the heat transfer conditions rather than to increase the power of the source. This will ensure an increase in both furnace productivity and its energy efficiency.

Let us illustrate the aforesaid by an obvious example. If a deep vessel containing water is heated from above, the upper layer of water boils while the main mass of water remains cold. It could be explained by the fact that stagnant water conducts heat poorly, and that hot water is lighter in weight than cold water and stays on the top. If under such conditions the power of the heat source is increased, then the entire additional power is used on an increase in the boil-off rate of the top layer of water, i.e., an increase in the amount of vapor generated per unit time. The rate of heating of the lower water layers remains practically unchanged.

When the vessel is heated from below, the heated water rises to the top, while the cold water goes down. The whole volume of water is stirred intensively and is quickly heated up to the required temperature, although the power of the energy source is several times lower than that of when heating from above. Correspondingly, the energy consumption for heating is reduced. In this case, the intensity of heat transfer from the top water layers to the lower ones is an inherent factor limiting the power of energy source. With water stirring, the heat transfer intensity increases many-fold, which makes it expedient to sharply increase the power of the energy source for the purpose of acceleration of water heating.

The same situation is observed in the case of heating the bath in electric arc furnaces, open-hearth furnaces, and other hearth furnaces. The baths of these

furnaces obtain the greater part of the heat supplied by the external energy sources from above: mainly from the electric arcs in the EAFs and from the burner flames in the open-hearth furnaces. Switching to high-power electric arc furnaces would not have been justified, if, concurrently with increasing the power, the measures were not taken to optimize the conditions of heat transfer from the arcs to the bath by means of submerging the arcs into the metal or in the foamed slag.

In open-hearth furnaces, increasing the power of the burners ensured substantial reduction of tap-to-tap time and increase in productivity, but only after successful intensification of heat transfer from the flames to the liquid bath by means of extensive use of oxygen. Before that, the increase in the power led only to excessive fuel consumption, while the tap-to-tap time was shortened insignificantly. A huge difference between the power level of the wall oxy-gas burners in the EAF and of the converter burners can also be explained by very different conditions of heat transfer from flames to scrap in these units, Chap. 6, Sect. 6.5.2.

All of the raised above issues related to the effect of heat transfer conditions on power level of external heat energy sources in the EAFs will be examined in detail in corresponding chapters. But the following fundamental conclusions can be made right now. Indeed, it is the heat transfer processes that limit the possibility of further increasing of EAF's productivity due to increase in the power of electric arcs and oxy-fuel burners. These same processes, basically, determine the energy efficiency of the EAF. When increasing the power of the heat generation sources, it is necessary to increase correspondingly the intensity of the heat transfer processes. Otherwise, the heat absorption rate can be insufficient, thus leading to unjustified increase in heat losses and energy costs. On the other hand, the very fact of improving the heat transfer conditions ensures an increase in both productivity and energy efficiency of the EAF with the same power of external heat sources.

It should be emphasized that in contrast to eliminating bottlenecks caused by external limiting factors, increasing the intensity of the heat transfer appears to be a far more complicated problem, which requires some new original engineering solutions. The total consumption of electrical and chemical energy in the EAF is still too high as compared to that of theoretically required. Too little attention was paid to this aspect of the process at the early stages of electric steelmaking. However, at present, due to a sharp increase in the price of all basic kinds of energy, as well as due to a shortage of energy in many regions and drastic toughening of environmental requirements, improvement of power engineering of electric arc furnaces becomes a matter of utmost importance. On the other hand, this is the direction that ensures the greatest potentialities for improving the process.

A sufficiently profound understanding of basic principles of heat transfer processes as applied to the processes taking place in the furnace is necessary for the critical analysis of innovations developed in this field. The technical literature examines the relevant problems in detail. However, such literature is not always accessible to those readers who have got no special education. In order to overcome this difficulty, the next chapter contains a brief presentation of basic heat transfer laws outlined in elementary form. Fundamental formulae and reference data required for calculations of heat transfer using the simplified methods are also presented.

Such calculations help to quickly resolve the problems related to estimating the innovations aimed at improving the thermal performance of the EAF. Studying this chapter would help the readers to carry out such calculations on their own.

Reference

1. Glinkov MA (1970) Thermal performance of steelmelting baths. Metallurgiya, Moskow

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