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Scientific Basis for Selection

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Preface to the Second Edition

The efforts of the developers of innovations for EAFs have intensified significantly in the last several years. This was caused by tightening of economic and environmental requirements to steelmaking. Development of new processes and new types of the furnaces was a way to meet this challenge. 400 ton capacity furnaces with the 240–300 MVA transformers have been developed and implemented. Productivity of these furnaces exceeds 360 t/h. Even on 120-t EAFs productivity level has reached over 200 t/h. A new promising process namely continuous melting of scrap in liquid metal has been implemented not only in the conveyor furnaces (Consteel furnaces), but in the shaft furnaces as well. New methods of scrap charging in the shaft furnaces have been developed which have great technological and environmental advantages. Consteel furnaces started using not only the heat of off-gases for scrap preheating but the burners as well.

The absence of the unbiased comparative analysis of new furnaces and technological processes makes difficult choosing between them, since the advantages of innovations are advertised, whereas the deficiencies are concealed. Potential users of the abovementioned innovations really need such analysis. The authors' works regarding these important issues were not yet finished by the time of the first edition of this book. That is why the second edition became a necessity.

The promising process of continuous melting of scrap in liquid metal, its advantages, and limiting factors are reviewed in detail in the Chaps. 1, 6, and 7 of the second edition. The performance indices of the conveyor and shaft furnaces using this process as well as heating of scrap by off-gases are compared to those of the modern EAFs operating without scrap preheating. The root causes of low energy effectiveness of heating of scrap by off-gases are discussed, and rationale for turning away from such heating is given.

Developed by the authors design concepts of fuel-arc furnaces (FAF) with continuous scrap melting and its preheating up to 800 °C by powerful oxy-gas burners either on a conveyor or in a shaft are suggested. In FAF, electric energy consumption is reduced to 200 kWh/t with gas flow rate of 20 m^3/t. Such furnaces can successfully compete with the most advanced modern EAFs and replace them. In the new edition, the latest innovations and other up-to-date information are added to the Chaps. 1, 10, and 14, etc.

The authors express their gratitude to the readers who gave their feedback. All their observations and considerations are taken into account in the second edition of the book. The authors thank Ch. Baumann and I. Falkovich for their help and cooperation. Our special gratitude goes to G. Toulouevskaia for the great work she did for preparing of this publication.

The Authors

Preface to the First Edition

Selection of innovations for each plant as well as selection of directions of further development is one of the crucial problems both for the developers and for the producers of steel in EAF. Ineffective selection leads to heavy financial losses and waste of time. In practice, this happens quite frequently.

The main objective of this book is to help the readers avoid mistakes in selecting innovations and facilitate successful implementation of the selected innovations. The entire content of the book is aimed at achieving this objective. This book contains the critical analysis of the main issues related to the most widespread innovations in EAF. The simplified methods of calculations are used for quantitative assessment of innovations. These methods are explained by numerous examples. Considerable attention is given to the new directions of development which the authors consider to be the most promising.

In the process of writing of the book, its content was discussed with many specialists working at metallurgical plants and for scientific research and development organizations. The authors express deep gratitude for their valuable observations and considerations.

A number of the important issues covered in the book are debatable. The authors would like to thank in advance those readers who will consider it possible to take the time to share their observations. Their input will be really appreciated and taken into account in further work.

Our heartfelt thanks go to G. Toulouevskaia for her extensive work on preparation of the manuscript for publication.

Ontario, Canada Yuri N. Toulouevski

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Introduction

Electric Arc Furnaces (EAF) are being greatly improved at a fast pace. Only 20–30 years ago, today's EAF performance would be impossible to imagine. Owing to the impressive number of innovations, the tap-to-tap time has been shortened to 30–35 min for the best 100–130 t furnaces operating with scrap. Hourly productivity increased by six times, from 40 up to 240 t/h. Electrical energy consumption got reduced approximately 1.8 times, from 630 to 340 kWh/t. Electrical energy share in overall energy consumption per heat dropped to 50 %. Electrode consumption was reduced by about six times, Fig. 1. One might expect such performances should be normal for most of steelmaking shops in the immediate future.

The technological function of EAF was drastically changed. All the technological processes providing both steel qualities required and its special properties have been moved out the furnaces to secondary ladle metallurgy equipment.[1] The necessary increase in furnace productivity could not be achieved without this revolutionary change in EAF steelmaking. The main technological processes in the modern furnaces are melting of solid charge materials and heating of liquid bath. It is precisely these substantial thermal-energy processes that now define furnace productivity. To get these processes going, it is necessary to obtain heat from other kinds of energy (electrical or chemical) and transfer it to zones of solid charge or liquid bath. This is why the electric arc furnaces themselves and the processes in them are reviewed in this book mainly from the unified thermal-energy point of view.

These furnaces turned to be very flexible in terms of charge materials selection. They could readily accommodate to melting in various combinations steel scrap, pig iron and hot metal, and reduced iron as pellets or briquettes. In the majority of furnaces, metal charge consists of scrap with small additions of pig iron. Traditionally, scrap is charged into the furnace from above as a single charge or in two-three portions. Only at the so-called Consteel furnaces and at certain shaft furnaces, scrap is practically continuously charged by means of a conveyer or a hydraulic pusher via a furnace sidewall door. The wide variety of innovations being

[1] These processes and equipment are not considered in the book.

offered by the developers for each particular case corresponds to the various furnace operation conditions.

Changes in heat techniques, furnace designs, and equipment are taking place at a fast pace. Every year, new technical solutions are offered and widely advertised. Steel manufacturers have difficulty navigating through the flood of innovations. Under steep competition, advertisement information is somewhat biased and incomplete. This makes selection of innovations for solving particular problems even harder. It is not easy to decide which information is trustworthy enough. But it is much more difficult to decide what to select: an innovation which was already proved by practice or it is better to take a risk of the first realization which in the case of success promises maximum economical effect. Frequently, the cost of new technologies exerts the decisive influence on this selection. Certainly, the price is one of key criteria. But the other not less important factors such as, for instance, a new equipment reliability have to be taken into consideration. Therefore, when being based for the most part on a price, a serious error can be made.

What could help to carry out unbiased analysis of innovations and select those which could yield the best results for particular circumstances of a given plant? First of all, comprehensive understanding of mechanisms and basic laws defining the main processes of the EAF heat is required. The modern concepts of these processes are presented in numerous magazine papers and reports from technical conferences which are held worldwide on a regular basis. For a practical steelmaker, it is hard to get reliable general information necessary to solve specific practical problems. Meanwhile, the knowledge of general simplified yet correct in principle concepts is sufficient for decision making. These general concepts are currently commonly accepted. Without compromising scientific strictness, these principles are discussed in this book at the level easy to understand for the readers who do not have an adequate background in this field.

Data on effectiveness of any proposed innovation must not contradict proven principles of the processes of the heat. If such a contradiction takes place, a proposal should be excluded from further consideration. Regretfully, experience proves that innovations which do contradict to the basic principles are proposed rather frequently.

A typical case can be shown. Up to this point, various methods of bath oxygen blowing are proposed in order to provide carbon oxidation inside the bath not to carbon monoxide CO as it takes place in reality but to carbon dioxide CO_2. If this would be possible, both heat amounts released in the bath and bath heating rate could be increased several times. However, according to the basics of physical chemistry of steelmaking processes, formation of CO_2 in presence of liquid iron is possible only in practically insignificant amounts. This basic principle was responsible for the failure of all attempts to oxidize carbon in steel bath to CO_2. These attempts were repeatedly undertaken in the past in both open hearth furnaces and oxygen converters.

This example demonstrates that historical approach to the analysis of innovations proposed is very helpful. Such an approach is widely used in various chapters of this book. In certain cases, data, obtained not only in the modern

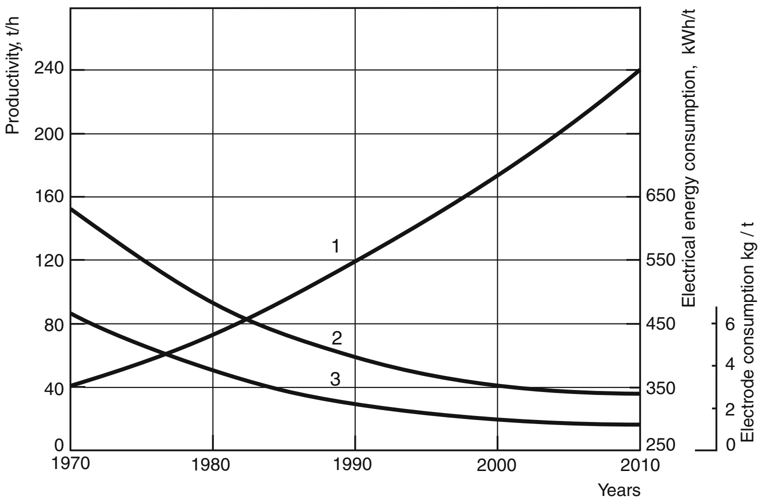

Fig. 1 Improvement in the 120-t EAF performances. *1* productivity, t/h, *2* electrical energy consumption, kWh/t, *3* electrode consumption, kg/t

steelmaking units but also in the obsolete open hearth furnaces, are used. When evaluating innovations for electric arc furnaces, the experience from open hearth furnaces as well as from converters proves to be highly useful. This is particularly relevant for the results of scientific and industrial studies of oxygen blowing in open hearth bath since the studies similar in scale, accuracy of experimental procedure, and resultant effectiveness have not been conducted in EAF.

Simplified calculations should be used for the preliminary comparative evaluation of innovations. Such calculations can be done manually by using regular calculators. Their accuracy is quite sufficient for the purpose pointed out. In many cases, the accuracy is not inferior to the accuracy of calculations which use complex methods of mathematical simulation. It can be explained due to the fact that often the input parameters for calculations are known quite approximately, and the accuracy of final results cannot exceed the accuracy of the input data regardless of calculation technique applied. In this regard, the mathematical calculations are similar to millstones: whatever you pour in that what you will get.

It should be emphasized, that carrying out even the very simple calculations greatly promotes comprehensive understanding of physical basics of processes and effects produced by various factors. Using "off the shelf" programs developed by means of the mathematical simulation of processes does not provide such possibilities. For the consumer, these programs are similar to a "black box" which does not reveal the mechanism of the process. The "black box" produces the final result but does not allow judging the conformity of the calculation to all the conditions of the specific case. Therefore, common "off the shelf" programs must be used with a great caution for evaluation of specific innovations.

When evaluating innovations which require heat balances of EAF, it is necessary to calculate thermal effects of exothermic reactions of oxidation of carbon, iron and its alloys. These thermal effects strongly depend on temperature of the initial substances and chemical reaction products. In a series of important cases, an effect of temperatures is not taken into account or it is not completely considered in the tables available to the readers. This leads to significant errors in calculations. In this book, an accurate and universal method, which is appropriate in all cases, is offered to determine influx of chemical heat. It is based on so-called method of full enthalpies and is very convenient for practical use.

Currently, most of innovations for EAF are aimed at the development of means and methods providing further intensification of processes of solid charge melting and liquid bath heating. Calculations in this field require knowledge of processes of heat transfer as well as hydro- and aerodynamics. To help readers mastering such calculations, several chapters containing required minimum of information in these fields of science are included in the book. This information is presented in a rudimentary form yet not compromising strict scientific meaning. Formulae for calculations are given in simplified form convenient for practical computing. Nevertheless, in doing so, the accuracy of calculations is maintained. Application of these formulae is illustrated by a large number of examples for analysis of innovations. Getting familiar with material in this book will allow the reader to perform required calculations on his own. In order to facilitate still further the performance of calculations, reference data needed for calculations are given in the book. This permits the readers to do away with the problem of searching for such data in various handbooks.

The book covers a wide variety of topics ranging from scientific concepts to state-of-the-art improvement practice of steelmaking in EAF. The book also contains new, progressive, in authors' opinion, ideas on key issues regarding intensification of the heat such as scrap heating using high power oxy-fuel burners, deep bath blowing with oxygen and carbon using high-durable tuyeres, etc.

Significant attention is given to analysis of various directions of automation of the energy modes control of the heat. The descriptions of different automated control systems are drawn up by their developers according to the same principle and in essence differ only slightly from each other. Usually, the system functions are enumerated in detail. For example, the system controls the consumptions of electrical energy, oxygen, and fuel ensuring their savings and the increase in furnace productivity. But there is no information on how this is being done or on a specific algorithm (mechanism) of the system operation. Therefore, both estimation and selection of innovations in this field present great difficulties for metallurgists. The method for comparing the automation systems based on analysis of information used for controlling the heat is outlined in this book. This method provides a means for easy understanding of real and alleged advantages of a particular system as well as for making a justified decision.

The last chapter of the book deals with environment protection from gas and dust emissions of arc furnaces. A problem of reduction in energy gas evacuation costs is reviewed with consideration for current tendencies.

You can assess this book based on its contents. It is addressed to a wide range of EAF-steelmakers and all other metallurgists related to this industry. This range includes, among other, three categories of specialists: those who have to effectively use innovations in day-to-day practical work, those responsible for selection of innovations for their factories, and the developers of new processes and equipment for EAF. The book can also be used as a textbook for students of all levels studying metallurgy.

Chapter 1
Modern Steelmaking in Electric Arc Furnaces: History and Development

1.1 General Requirements to Steelmaking Units

The structure of modern steelmaking has been formed gradually during the last 100 years. In this period, due to many different reasons, the requirements to steelmaking units have changed substantially. Some production methods have appeared and developed, while other ones have become noncompetitive and have been rejected. All these changes were interrelated and influenced each other. The understanding of electric steel production development and its prospects can not be complete if this process is studied separately setting aside the development of steelmaking in general. Therefore, it is necessary, even if briefly, to review the history of not only electric arc furnaces but also other steelmaking units competing with each other.

Steelmaking units should meet a number of requirements that could be classified into four groups in the following way:

1. Process requirements ensure the necessity to produce various steel grades of required quality.
2. Economic requirements call for reduction of manufacturing costs so as to increase profitability and competitiveness of products.
3. Environmental requirements do not permit any excessive environment pollution, the level thereof being governed by state regulations.
4. Health and safety requirements exclude the use of physically and psychologically straining labor which, at a certain stage of social development of society, becomes unacceptable for the population of a given country.

In any case, all innovations introduced in steelmaking have always been aimed at fulfilling some or all of the above mentioned requirements. However, the influence of these requirements has been changing greatly in the course of time.

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1.1.1 Process Requirements

Up to the middle of the twentieth century, the most important changes in steelmaking were instigated by these very requirements. At the very beginning of the century, they led to development and wide spread of the electric arc furnaces (EAFs), since these units made it possible to easily achieve highest temperatures and ensured the best conditions for producing of high-quality alloyed steel grades and alloys. Previously, such metal could be produced by the crucible method only. Due to its inefficiency and too high requirements to the purity of raw materials, this method could not compete with the EAF process. A demand for special expensive steels and alloys with particular properties was quickly increasing. Electric arc furnace became the main supplier of such metals, though it was also used for production of relatively small quantities of common steel.

The process requirements were also a reason for replacement of acid and basic Bessemer converters with open-hearth furnaces. Due to increased nitrogen content, the quality of steel produced in the air-blast converters was greatly inferior to that of the open-hearth steel. As a result, the open-hearth method has become prevailing method of steel mass production, right up to the development of oxygen converters and even somewhat later.

The process requirements ceased to have a substantial effect on the relative competitiveness of basic steelmaking units when the ladle furnaces were introduced and became widespread as molten metal treatment units. At present, both oxygen-blown converters and EAFs usually produce semi-products of preset temperature and carbon concentration. This metal is treated to reaching the final chemical composition, refined by removing dissolved gases and non-metallic inclusions therein, and heated up to optimal temperature in ladle furnaces and other secondary metallurgy units.

Practically every steel grade can be produced by this way. The only obstacle encountered when producing some specific steel grades in EAFs is the contamination of scrap with copper, nickel, chrome and other residual contaminants which can not be removed in the course of processing of the finished steel. Permissible content of these contaminants is strictly limited in quality steel grades. This obstacle is overcome by means of more careful scrap preparation as well as by partial substitution of scrap with hot metal or products of direct iron reduction. Recently, such products are used in electric steelmaking rather widely.

1.1.2 Economic Requirements

The cost of scrap and ferroalloys amounts to approximately 70% of the general costs in EAFs operating on scrap. The so-called costs of operating constitute the rest 30%; the cost of electrical energy, fuel and electrodes account for about 40% of the latter. There are three possible ways of reducing the costs:

1. By cutting down specific consumption of charge materials, energy-carriers, refractory materials etc. per ton of steel.
2. By increasing output and thus reducing specific manufacturing costs, such as maintenance staff costs etc.
3. By replacing expensive charge materials and energy-carriers with cheaper ones.

Innovations developed in the first direction are always justified as well as those in the second one. For more than half a century, the main direction of development of electric arc furnaces is increasing of their productivity. Almost all innovations, implemented in this period of time, were aimed at this problem. Without solving this problem the EAF could have never become the very steelmaking unit which along with oxygen converter is a determinant of world steelmaking.

Excluding the cost of metal charge the productivity is a parameter on which the entire economics of steelmaking process depends to the greatest degree. As a rule, when productivity is increased, manpower and maintenance costs are reduced, as well as costs of electrical energy, electrodes, fuel, refractories and other so-called costs of operating, including overall plant expenditures.

Electric arc furnaces are mostly intended to be installed at mini-mills where they determine productivity of the entire plant. Increasing output of mini-mills to one-two million of tons per year or even more had decisive effect on the maximum productivity level of EAF. It is most reasonable to equip steelmaking shops at such plants with one furnace, two at the maximum. Such organization of production allows minimizing manpower and operating costs in general.

If the shops are equipped with a number of furnaces then under conditions of extremely high pace of operation it is impossible to avoid some organizational delays. Any disruption of the preset production pace at one of the furnaces adversely affects other furnaces thus reducing significantly the shop productivity and that of the plant as a whole. Therefore, preference is given to the shops equipped with one furnace, even in the cases when required output exceeds 2.0–2.5 million ton per year.

Innovations developed in the third group are not always justified. Prices on materials and energy-carriers are subjected to rather abrupt fluctuations so that they are difficult forecast. In different countries, they can change dissimilarly and even in the opposite directions. That is why the innovations, determined only by a price difference, are associated with relatively high risks, especially when they are aimed for long-term and wide spread.

Let us discuss a number of examples. Scrap was substantially cheaper than hot metal for a long time nearly everywhere. Under such conditions, increasing amount of scrap re-melted in oxygen converters aiming at reducing hot metal consumption, could promote a significant increase in converter steel profitability. To achieve this various methods were developed to introduce additional heat into converters, such as scrap preheating by powerful oxy-fuel burners, introduction of coal and other carbon-containing additives into the charge, post-combustion of carbon monoxide evolved in the converter etc. Developing out and mastering these innovations was associated with significant difficulties. To overcome these difficulties long-term extensive industrial research accompanied by vast spending was conducted in a number of countries.

However, the interest in all these innovations was gradually declining as scrap price was increasing and approaching the price of hot metal. Therefore, replacing hot metal with scrap in converters was stopped. On the contrary, in the recent years, hot metal started to be used in EAFs in increasing amounts. This assured significant reduction of tap-to-tap time and electrical energy consumption, and also promoted production of such steel grades which require charge rather free from foreign contamination.

At present, a situation similar to that of replacing hot metal with scrap is developing with regard to innovations aiming at substituting electrical energy with the natural gas energy in EAFs. Just recently, this aim was justified by low cost of gas compared to electrical energy. At first glance, such price ratio could not change substantially, since a significant share of electrical energy is produced at thermal power plants using gas. However, in reality in most of countries, the price of natural gas was rising many times more quickly than the price of electrical energy. For example, in the USA the price of natural gas has increased by more than four times since 1990 to 2008. This limited use of oxy-gas burners in EAFs. Presently, in the North America, the prices for natural gas have sharply dropped down to about the price level that has taken place in the early twenty-first century due to commercial development of a shale gas deposit. A new economical situation contributed to the fact that replacing electrical energy with energy from natural gas in EAFs has again become an urgent problem.

Attention has to be given to the fact that increase of price of scrap and natural gas cannot be explained by alleged rising shortage of these resources. On the contrary, the supplies of unused dormant scrap are constantly growing in the majority of the developed countries. For instance, presently in the US supplies of steelmaking-worth scrap exceed 800 million tons. Natural gas price is growing even in the countries where gas reserves are practically unlimited. The increase in the mentioned prices is not linked directly to either scrap preparation costs or gas production and transportation costs.

Along with long-term rising trend, world scrap prices are subject to very sharp fluctuations, depending on the demand. Scrap price is growing during the years of industrial development and steelmaking increase, while it is falling in the period of industrial stagnation. In some years, scrap prices have changed repeatedly by 1.5–2 times. Absence of these fluctuations cannot be guaranteed in the future; they obstruct investments in scrap-processing industry.

The technical advantages of using scrap and natural gas in steelmaking are beyond any doubt. It was calculated that each ton of steel produced out of scrap instead of hot metal provides saving of approximately 1100 kg of iron ore, 640 kg of coal and 2.9 MWh of energy. However, purely technical considerations are not prevalent in this case. The analysis of the actual situation leads to the conclusion that a very contradictory and unpredictable practice of formation of prices on scrap, hot metal and energy-carriers is not caused by objective technical reasons but is dictated by transient short-term considerations both of political and purely commercial nature. These considerations are formed under the influence of many factors.

The world scrap market is rather sensitive to situation with sharp fluctuations in some countries with highly-developed steelmaking, especially in those of them where the government exerts substantial influence and even strictly controls scrap import and export. It must be taken into account that scrap could be considered not only as waste to be disposed, but also as raw material resources of great strategic significance. All this influences the prices and rather negatively affects general technological progress in steelmaking.

Prices of various types of metal charge and energy-carriers are subject to sharp fluctuations with time and country to country; therefore the price factor should not be used as a unique criterion that would allegedly divide all new developments into promising and prospectless. The very processes, which are unprofitable now, could prove, in the nearest future, not only economically sound but also the most efficient in some countries or maybe everywhere. Hence, it is quite necessary to pay considerable attention to developing innovations aimed at radical improving such objective performance parameters of EAFs as output, energy efficiency, environmental protection level, operational reliability etc., even if today's prices of resources required for EAFs seem to be unacceptable. Entire history of technological development proves this point of view.

1.1.3 Environmental and Health and Safety Requirements

In the first half of the last century, the effect of these factors was practically insignificant. Afterwards, it started to rise gradually. In the recent decades, steelmakers, especially in developed countries, encounter, increasingly stringent restrictions regarding emissions of CO_2, CO, NO_x, dioxins and other harmful gases and dust. There is a point of view rather worthy of notice that environmental requirements are observed to become more and more stringent to a degree that in some cases is beyond any reasonable limits. Further even rather insignificant reduction of emissions requires multiple cost increase from steelmakers, although steelmaking is not by far the main air pollution source on a national scale.

According to the data provided by Thyssen Stahl AG, dust emissions were reduced at the company's plants in the 1960s from 18–19 to 2 kg per ton of steel while the costs amounted to 100 DM per ton of dust. In the 1970s, dust emissions were further reduced by 0.45 kg per ton of steel while the costs amounted to 3,000 DM per ton of dust. In the early 1980s, emissions were further reduced by 0.5 kg per ton of steel which had required an increase in cost up to 10,000 DM, and to satisfy the new requirements it would take more than 100,000 DM per ton of dust [1].

At present, cost of environmental protection amounts to 15% of a new plant's price. Extremely stringent environmental requirements cause moving steelmaking plants from Europe and the USA to Third World countries where these requirements are much less strict. Mini-mills are being built equipped with EAFs, since, along with other decisive advantages compared to the integrated plants, emissions into atmosphere are significantly lower when producing steel from scrap. At integrated plants CO_2 emissions amount to 1825 kg/t of liquid steel. For EAFs where the charge consists of 50% scrap and 50% hot metal these emissions are 1717 kg/t, and at furnaces operating on 100% scrap those are only 582 kg/t. Besides, water pollution decreases by 40% approximately when producing steel at mini-mills.

It should be emphasized that using hot metal in EAFs to a great degree strips them of their environmental advantages. Some rather efficient innovations in EAFs such as slag foaming by carbon injection or use of oxy-gas burners provide significant reduction of electrical energy consumption but increase emissions of CO_2. Such innovations should be evaluated, from the environmental requirements point of view, not only within the bounds of steel melting plants but also on a national scale, taking into consideration the reduced demand for electrical energy for steelmaking and, consequently, reduced emissions at the thermal power plants.

The significance of health and safety requirements was growing concurrently with increased effect of environmental factors. Presently, in the US and Europe mostly immigrants from the Third World countries are employed at the positions requiring hard physical and mentally demanding labor in steelmaking shops. This, in turn, leads to complex social problems. Therefore, more attention is paid to the innovations aimed at elimination of hard physical labor by changing the processes, introducing mechanization and automation thereof.

The health and safety requirements affected significantly the very structure of steelmaking. Contrary to the well-known opinion, open-hearth steelmaking was replaced by oxygen converter method not so much for economic reasons as for social ones. There was only a slight difference between the cost of steel produced by open-hearth method and oxygen converter method. According to various estimates, the difference amounted to approximately one dollar per ton of steel. However, labor conditions in open-hearth shops compared to those in oxygen converter shops were extremely gruelling, especially during furnace repairs.

Shrinking and later complete stopping of open-hearth steelmaking caused, in most countries, sharp increase of available scrap resources, since a scrap share in open-hearth charge was approximately 40–45% whereas in the converter charge it was about 20–25%. That was one of the key factors which caused the appearance and fast spread of mini-mills equipped with electric arc furnaces operating on scrap.

The examples presented above show the close connection of all changes in the structure of steelmaking. Under the pressure of the requirements discussed above and within the evolving economic conditions these changes have led eventually to the modern steelmaking in EAFs.

1.2 High-Power Furnaces: Issues of Power Engineering

1.2.1 Increasing Power of EAF Transformers

This innovation plays a decisive role in sharp shortening tap-to-tap time and increasing EAF productivity per hour. The first so-called ultrahigh-power (UHP) furnaces appeared in the US in 1963. These 135-t furnaces were equipped with 70–80 MVA transformers, specific power amounting to 520–600 kVA/t. Previously, specific power of 50 to 100-t furnaces did not exceed 200–250 kVA/t. Due to their successful operation UHP furnaces became widespread rather quickly, and their specific power was increased to 1000 kVA/t.[1]

In recent years, furnaces of 300 to 400-t capacity have gained some spread. In such furnaces, the specific transformer power is reduced despite a sharp increase in its absolute power. It is mostly explained by a limited current carrying capacity of electrodes, Sect. 1.2.3. The very powerful transformers in the world have been installed at a 420-t EAF with a power of 240 MVA in Gebze [2], and at a 300-t EAF with that of 300 MVA [3] in Iskenderun, Turkey.

At the first stage of UHP furnaces, increase of their average monthly and annual productivity was limited by to sharp deterioration of durability of sidewalls and roof refractory lining and subsequent increase of downtime during repairs. This obstacle has been eliminated by replacing up to 85% of total lining area with water-cooled panels.

Hourly productivity of the furnace at the given capacity is inversely proportional to overall tap-to-tap time τ. The value of τ represents a sum of two components: power-on furnace operation time when arcs are on (τ_{on} period) and so-called power-off time of operations requiring electric arc switching-off (τ_{off} period) $\tau = \tau_{on} + \tau_{off}$. The τ_{off}-operations include tapping, closing of taphole after tapping, scrap charging by one or several baskets etc. By increasing electric arc power, only the duration of scrap melting and liquid bath heating (τ_{on} period) is reduced. Therefore, if duration of power-off period τ_{off} is too long and τ_{on}/τ ratio drops below 0.7, using UHP furnaces become economically inexpedient.

The higher the power is the greater part of the tap-to-tap time should be taken up by the power-on furnace operation time, and the closer the average power value within τ_{on} time to the maximum value should be. Any power reduction, occurring within that period, decreases EAF's productivity. When UHP furnaces were implemented, these requirements significantly promoted reducing the duration of power-off operations and transferring process operations, which required reduced power, from furnaces to secondary ladle metallurgy units. Such process operations which increase the tap-to-tap time significantly are desulphurization of steel and refining it to the required chemical composition. As it has been already mentioned, it would be impossible to achieve the current parameters of UHP furnaces without

[1] See Sect. 1.2.2 on difference in measuring EAF power in VA (volt-ampere) and watts, W.

converting them over to producing semi-product. Further below, these furnaces will be referred to as "high power".

1.2.2 Specifics of Furnace Electrical Circuit

An increase in electrical power aggravates not only water-cooled elements and durability problems of refractory lining associated with the increase of thermal radiation from electric arcs. Problems of electrical nature caused by the specifics of the furnace electrical circuit arise as well. This circuit includes electric arcs, electrodes and so-called secondary circuit connecting electrodes with the furnace transformer. The secondary circuit consists of busbars, flexible cables and current-conducting arms with electrode clamp. Without going into details let us discuss only the basic electrical specifics of the circuit.

Overwhelming majority of EAFs operates on alternating current (AC). As it is well known, alternating current I, measured in amperes (A) and voltage U, measured in volts (V), change in a sinusoidal manner. If the current passes through an active resistance[2] both values reach their maximum and pass zero simultaneously, i.e., they coincide in phase, Fig. 1.1. In this case, consumed actual electrical power P, measured in watts, W, is converted entirely into heat, $P = U \cdot I$.

If the AC circuit includes not only active resistance but also inductive impedance, e.g., a conductor wound around an iron core then the maximum and minimum values of current and voltage will not coincide in phase, Fig. 1.1, curve a. In that case, electrical energy is not entirely converted into heat; a part thereof is consumed to form an alternating electromagnetic field in the space surrounding the electrical circuit. Phase shift in such circuit is characterized by the so-called power factor $\cos \varphi < 1$. The actual power consumed by the circuit and converted into heat is calculated by formula $P = U \cdot I \cdot \cos \varphi$. Electric furnace circuit is characterized by certain inductance. Therefore, the EAF power is usually expressed both in actual power units, MW, and in total power units, megavolt amperes, MVA. P, MW = P, MVA. cos φ.

The electric circuit specifics are determined first of all by the specifics of the arcs themselves. For simplicity sake, let us discuss first the processes which occur in a direct current (DC) arc; similar processes take place in high power AC arcs. DC arc column between a graphitized electrode (cathode) and either scrap lumps or a furnace bath, is high-temperature plasma consisting of neutral molecules and atoms of various gases and vapors present in the furnace freeboard, as well as of electrically charged particles, i.e., of electrons and ions. Current transfer in the arc is conducted mainly by electrons emitted from the cathode heated up to a high temperature. According to various estimates, in high power furnaces, the

[2] For alternating current, active resistance is, for instance, the resistance of straight wire the electromagnetic field energy of which could be ignored.

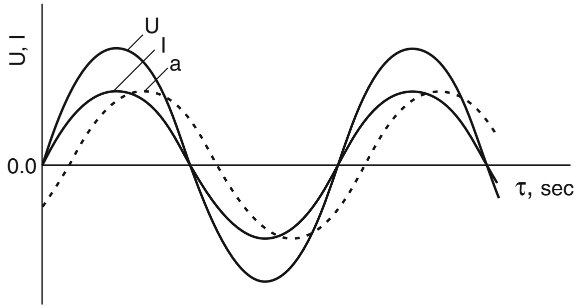


Fig. 1.1 Curves of voltage *U* and current *I*. *a* phase shift

temperatures in the arc column range within 6000 to 7000°C and current density reaches several thousands of A/cm^2.

Arc column is compressed by electro-dynamic forces resulting from the interaction of the arc current with its own electromagnetic field surrounding the arc. The resulting pressure affects the liquid bath surface causing the arc to submerge into the melt to a certain degree. If the current increases electro-dynamic forces compressing the arc rise as well as heat energy concentration within the arc space and depth of arc submersion into the liquid bath.

Similarly to the regular conductors, e.g. metallic ones, arc voltage rises as its length increases. However, contrary to these conductors which obey Ohm's law stating linear dependence between voltage and current, active resistance of the arc decreases as current increases. Therefore, an increase in current does not require voltage rise. Such a nonlinear volt-ampere characteristic of the arc does not provide conditions required to stabilize arc discharge. The secondary circuit should have a certain resistance for stable arcing, active resistance in DC EAF, as well as inductance for the AC EAF. All the above stated with respect to the DC arc can be to a considerable degree applied to arcs in AC EAFs, considering values of current and voltage within each half-cycle, with taking into account inductance in the secondary circuit.

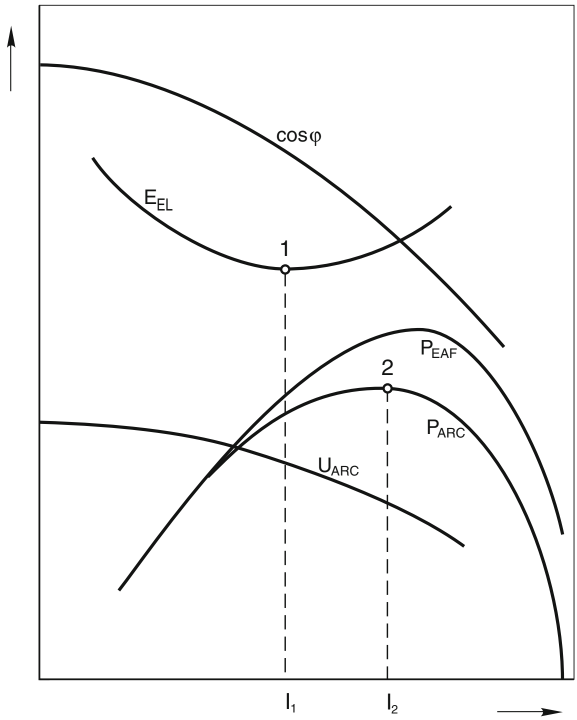
In the AC arc cathode and anode alternate at each voltage direction change. Either electrode or surface of scrap lumps or liquid bath serves as the cathode, by turns. In modern furnaces, the arc discharge does not cease as voltage approaches zero at the end of each half-cycle, since high power arcs have significant inertia regarding both conductivity and temperature condition of the arc column. However, the shape of arc voltage curves can significantly differ from sinusoidal. That difference is getting smoothened as power and current grow.

Arcing stability could vary significantly during the course of the heat. Immediately after charging a new basket of scrap, arcing takes place on the surface of separate scrap lumps which are continuously moving while the charge settles down. During this period arcs are not stable. Despite operation of automatic controllers the arcs break rather often as a result of sudden sharp increase of arc length. Arc discharge breaks occur also during short circuit when electrodes get in contact with scrap pieces. After the initial bore-in period, arcing is observed between the electrodes and the surface of molten metal collected at the bottom, and later, between the electrodes and the surface of formed bath. In this case, arc stability increases significantly. As arc current and power are increased their stability grows during all periods of the heat. The same is observed when scrap is preheated to high-temperature.

Since the arc volt-ampere characteristic is nonlinear, the entire electrical circuit of EAF becomes nonlinear as well. The processes taking place in this circuit as well as dependences between electrical parameters of the circuit are rather complex. These dependences are shown schematically in Fig. 1.2. With an increase of current I actual furnace power P_{EAF} and arc power P_{ARC} (P_{ARC} is lower than P_{EAF} due to power losses in the secondary circuit) change according to extremum curves, i.e. curves with a maximum. At the beginning, the P_{EAF} and P_{ARC} grow to certain maximal values and then fall quickly as current grows further. During short circuits, when currents are the highest the arc power drops to zero. Arc voltage U_{ARC} and power factor cos φ decrease steadily as current increases, Fig. 1.2. The power factor cos φ is close to 0.8 in the modern high power furnaces.

The dependence between current value I and electrical energy consumption E_{EL} is also of extremum nature. If only this kind of energy were used in the furnace, then to minimum energy consumption a certain current value I_1 would correspond. Current I_1 is considerably lower than current I_2, at which maximal arc power P_{ARC} is reached. It could be assumed approximately that maximum rates of scrap melting and liquid bath heating, i.e., maximal furnace productivity correspond to

Fig. 1.2 Electrical characteristics of EAF



maximal arc power. Thus, most economical mode of the heat as far as electrical energy consumption is concerned, does not match the mode of the maximum productivity as the former requires operation at lower current and lower arc power. It is basically impossible to combine these two modes.

The above mentioned principle is based upon the fundamentals of thermodynamics and is valid not only for EAF but also for all other types of furnaces. As the power of external energy source increases from low values corresponding to the furnace idling (in this case, actual power of electric arcs is meant), the thermal efficiency of the source first rises rapidly from zero to its maximum level and then starts dropping. This could be explained by the fact that further increase of useful, i.e. assimilated power falls more and more behind the total rise of the power source due to of the advanced growth of heat losses. These problems are discussed in detail in Chap. 5.

1.2.3 Optimum Electrical Mode of the Heat

Electrical mode is the program of changing, in the course of the heat, of such electrical parameters of the furnace circuit as current and voltage, arc power etc. The design of the furnace transformers allows changing these parameters stepwise within a wide range, whereas current and voltage may vary at the constant maximum actual power as well. Switching over the transformer voltage steps "on-load" is performed either automatically or by operator's command.

Since the introduction of high power furnaces, their electrical modes were developed based on the following general principle. At the period of melting solid charge, when scrap still shielded sidewalls against arc direct radiation, the maximum transformer power and long arc were used, i.e., high voltages at reduced currents. As liquid bath formed arcs were shortened gradually by reducing voltage and raising current. At final stages of the heat the furnace operated at reduced power with maximum currents which assured maximum submersion of the short arcs into the bath, the highest heat absorption by metal, and the lowest heat losses through water cooling the sidewall panels. Earlier it was assumed that the basic principles of such electrical mode are not subject to any revision [4].

However, affected by foamy slag technology introduced ubiquitously, Sect. 1.3.2, these principles have undergone fundamental changes. Instead of decreasing length of arcs in order to achieve their immersion in the melt through the increased current and pressure force of arcs onto the liquid bath surface, the level of the melt is raised and long arcs are covered with the foamed slag. This possibility has lead to the development of new principles of the optimum electrical mode of the heat.

Electrical power can be increased by increasing either current or voltage because the power is proportional to the product of these values. Both these ways are tightly associated with the problem of graphitized electrodes which is one of bottlenecks limiting further increase of electrical power EAFs. As current