Erwin Dötsch

Inductive Melting and Holding

Fundamentals | Plants and Furnaces | Process Engineering

3rd Edition

Vulkan Verlag

edition heat processing


ELEMENTS UNDER CONTROL
Refractory solutions based on expertise and experience

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FOREWORD

Induction technology for melting and holding continues to enjoy great importance in the production and processing of a range of metal materials. A new impetus for this environmentally friendly process has arisen from global targets for the reduction of CO_2 emissions which, as the percentage of renewable sources used for the generation of electricity continues to increase, unequivocally favour the use of electro heat rather than fossil energy sources for thermal production processes. This is true, in particular, of the primary users of inductive melting, namely the iron and steel foundries. One may not agree with the Federal German Environmental Bureau's claim that the cupola furnace is an obsolete and climate-harming piece of apparatus, but the trend toward inductive melting in foundries, one boosted by climate policy, is undeniable. High-performance induction furnaces developed specifically for steel production are of special interest in this context, in view of numerous conversions to inductive melting in major melting shops which were previously able to produce cost-efficiently only using the cupola furnace.

This title provides a sound basis not only for this specialised application, however. The book's overall layout has remained unchanged for this 3rd edition: an introductory examination of the fundamental principles of the induction process and a description of the technical equipment and the melting metallurgy of the different metals are followed by details of the metallurgical process technology of melting, holding and processing with induction systems in the ferrous and non-ferrous metal industries.

I am pleased to renew here my sincere thanks to the Board of Management of ABP Induction Systems GmbH, of Dortmund, which has now also made possible the 3rd edition of this work and which give me the opportunity of remaining in daily contact with ongoing developments in this field. My particular thanks also to all ABP colleagues for their ever-pleasing cooperation, which is reflected in updated form in this 3rd edition, for the benefit, as I hope, of all readers.

Dortmund 2018

Dr.-Ing. Erwin Dötsch

PREFACE

Inductive melting and holding are among the most important applications for electrothermal processes and are two of the most quickly expanding and best performing sectors of all applications for induction technology. Following the rapid growth of inductive melting during the 1960s on the basis of line-frequency technology, this sector underwent a renewed boom thanks to the development in the 1980s of suitable energy-supply systems for medium-frequency technology. The global importance of induction melting in iron foundries, in steelmaking plants and in non-ferrous metallurgical plants now continues to rise steeply.

The year 2009 saw the publication of the first edition of this specialised title, in which the author presented his expert knowledge, acquired during many years of work in the field of induction melting both in plant engineering and in various field applications, in detail and with strict practical orientation. The second edition (2013) incorporated the system- and process-engineering advances in induction melting technologies achieved during the intervening period. The third edition again constitutes a revised and updated version of this standard work for engineers, technicians and practitioners in melting shops and foundries. This specialist title has thus also been augmented with the topic of advanced cooling systems for high-performance crucible furnaces, including waste-heat recovery and utilisation, as well as recent developments in the energy-efficiency of induction furnaces.

The author has thus expanded the available expert knowledge in the field of inductive melting and holding to reflect the latest state of the art. This book, too, will without doubt provide excellent support for numerous specialists in their daily activities at universities and colleges, in Research & Development, and in practical application.

Prof. Dr.-Ing. Bernard Nacke

Managing Head of the
Institute of Electrotechnology
at the Leibniz University of
Hannover

GREETING

Dear Reader,

In times of digitalization you have to think twice before publishing the 3rd edition of a bound book.

However, the demand for the 2nd edition and the numerous inquiries into whether a new edition would be published in future finally convinced us to launch a 3rd edition.

This 3rd edition would not be possible without the dedication of Dr. Erwin Dötsch. He deserves my great respect and personal thanks for the hard work required to revise the previous edition by adding the latest developments in regard to technology and processes.

Based on my personal experience I can ensure that the state-of-the-art content and the practical writing are making this book so valuable.

When joining ABP three years ago "Inductive Melting and Holding" was a supportive helper to get familiar with our industry.

We hope that this book simplifies your first steps into inductive melting and holding and that we can thereby contribute towards generating enthusiasm among young, talented people for our exciting industry and its applications.

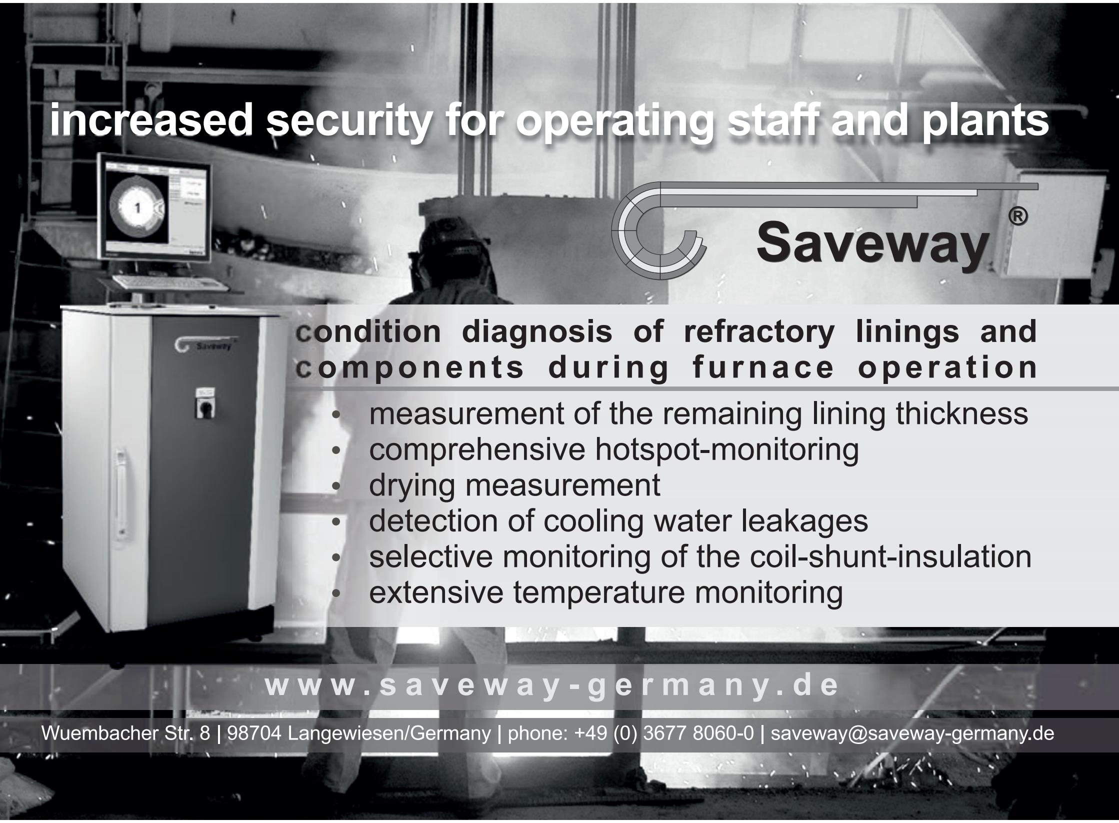
Please enjoy reading it.

With best regards and
Glückauf!

Yours,

Till Schreiter

CEO of
ABP Induction
Systems GmbH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1. Introduction

1. INTRODUCTION

Inductive melting and holding has found wide acceptance in metal producing and processing industries. Two main types of induction furnaces are deployed for this purpose: the induction channel furnace and the induction crucible furnace. These are depicted in diagram form in **Figure 1.1.**

The first technically feasible induction furnaces were based on the principle of the channel furnace [1]. Milestones were the first patent obtained by de Ferranti in 1887 and the construction of the first induction furnace in 1899 by the Swede Kjellin. In Kjellin's furnace, the melt is guided around the coil in a horizontal, open channel, hence the name "channel furnace". The open channel underwent further development, by the American Wyatt in particular, to become an enclosed refractory channel in a vertically standing U-form.

Induction crucible furnaces became significant to industry at the start of the 1930s with the development of high frequency furnaces, fed by motor generators, so-called rotary converters. A large number of such furnaces were installed over a period of just a few years in the USA, Russia and Europe with capacities of up to 8-t for melting iron and non-ferrous metal materials.

After World War II, there was firstly the development of high frequency (HF) to medium frequency (MF) crucible furnaces with the power being supplied through rotary converters or static frequency multipliers (triple or quintuple

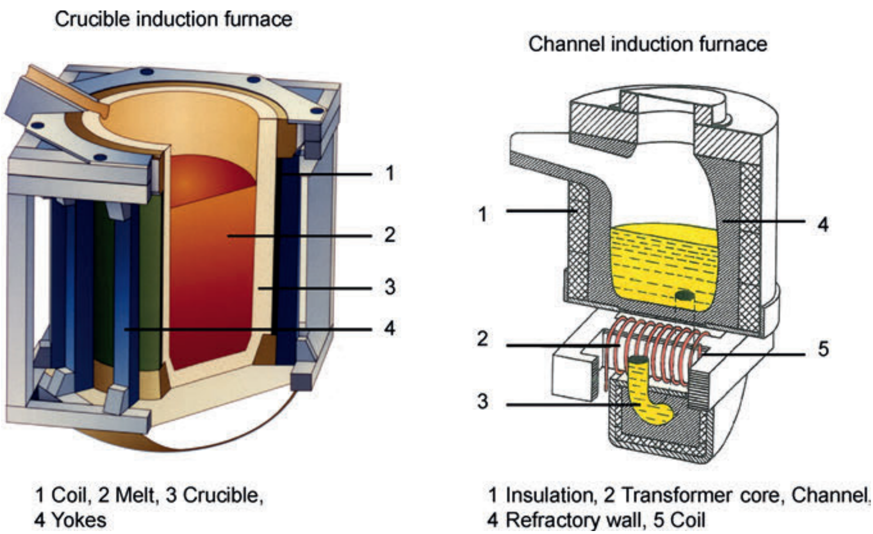

Figure 1.1: Diagram of an induction crucible furnace and an induction channel furnace

multipliers). Then came the era of the line frequency (LF) crucible furnace. With the advantage of being able to be connected directly to the 50 or 60 Hz mains electricity grid, the LF crucible furnace experienced a rapid development as a melting unit in the foundry industry. This progress reached its provisional peak in 1970 when 60-t furnaces were installed with a power consumption of 21 MW at an operating frequency of 60 Hz [2, 3]. Inductive melting thus came to be regarded in iron foundries as an economically viable technical alternative to cupola furnaces, while it was able to supplant the majority of gas and oil-fired plants for melting non-ferrous metals. A drawback was the heel operation required for economical power consumption. On the one hand, this allows only small tapping amounts, and on the other hand, it requires upstream drying of scrap metal for reasons of operational reliability.

Inductive melting was given a new impetus at the start of the 1980s with the development of the static frequency converter which, after the introduction of thyristor technology, was successful from a number of aspects: The efficiency of frequency conversion was raised from the 60 to 80 % at that time up to around 97 to 98 %. At the same time, high operational reliability and availability was achieved and procurement costs were cut by half. Compared to a line frequency furnace, the higher and more adaptable coil current frequency enabled a converter-fed crucible furnace with the same capacity to be operated at approximately three times the furnace power level and without heel, without lowering melting performance [4, 5].

In the case of channel furnaces, the furnace power levels able to be installed were restricted for a long time, mainly because the inductor refractories had inadequate service lives. Ground-breaking developments in the 1980s led to a significant increase in performance while extending the life expectancy of refractory linings, particularly for melting non-ferrous metals. Compared to crucible furnaces, induction channel furnaces nevertheless have a much lower specific power based on capacity, due to their construction principle. Their particularity lies in the fact that large volume furnace units can be constructed in siphon execution with an enclosed gas chamber. This type of furnace is accordingly well suited for storing larger volumes of molten iron. Moreover, channel furnaces can also be advantageously deployed for melting non-ferrous metals because their high electrical efficiency, in the form of low energy consumption, pays off well here.

2. Fundamentals

2. FUNDAMENTALS

2.1. Inductive power transmission

Power is transmitted in induction furnaces in that an alternating current is passed through a multi-winding coil to heat the charged material, usually an electrically conducting metal (**Figure 2.1**) [6]. The alternating current running through the coil creates an alternating magnetic field. Voltage flows through the feed material when it is introduced into this magnetic field in accordance with the law of induction, whereby eddy currents are created due to the conductivity of the metal. The inducted current heats the charged material in accordance with Joule's law and it becomes molten after a certain heating time.

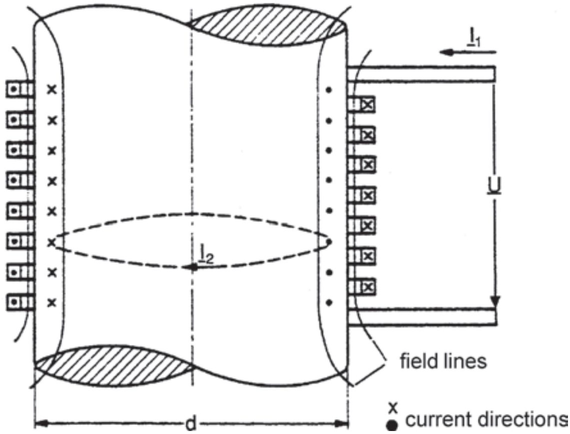

Figure 2.1: Principle of inductive energy transmission [6]

The eddy currents flowing through the feed material generate a secondary magnetic field which is opposed to the primary magnetic field. This causes the resulting magnetic field in the middle of the charge to weaken and thus the induction effect in the inside is reduced. The overlap of the magnetic fields displaces the current in the charge towards the outside. The skin effect causes the current density to decrease from the outside towards the inside (**Figure 2.2**). For an induction crucible furnace, the Equation (2.1) gives an approximation of the current density I at the distance x from the surface of the material

$$I_x(r) = I_0 \cdot e^{-r/\delta} \qquad (2.1)$$

The variable δ represents the penetration depth of the electromagnetic field and designates the distance from the surface, in that the current density decays

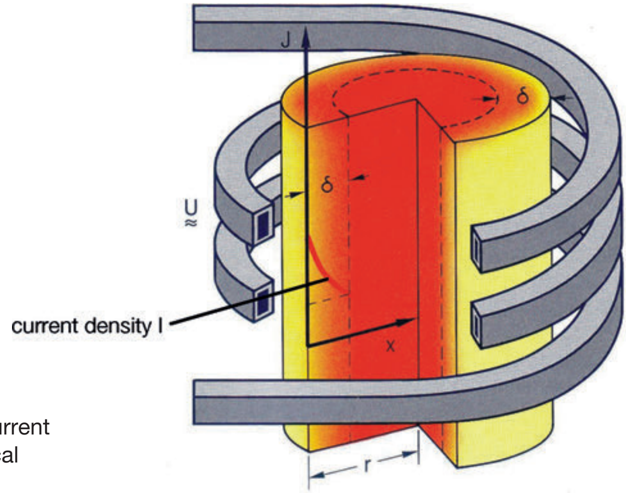

Figure 2.2: Course of current density within a cylindrical metal piece [7]

to 1/e of the surface value, thus to 0.37 - I_0. The penetration depth results from

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}} \tag{2.2}$$

In this equation, ρ is the electrical resistance of the feed material, μ its permeability and f the frequency of the coil current.

The penetration depth can be interpreted as an equivalent plane conductor thickness, as shown in **Figure 2.3**, through which a current flows that has the surface current density I_0 over the complete layer thickness.

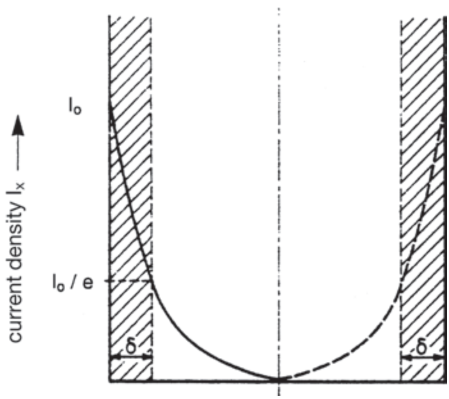

Figure 2.3: Course of current density during inductive heating [6]

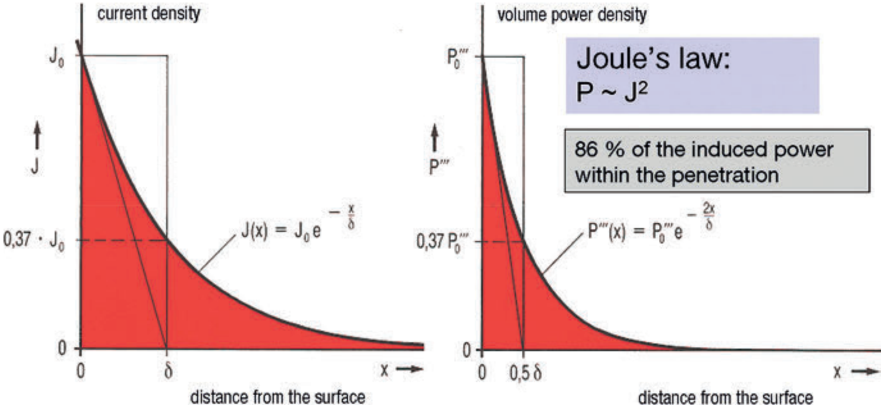

Figure 2.4: Course of current- and power density within the electromagnetic penetration depth [7]

In accordance with Joule's law, the power density is proportionate to the square of the current density. That is why the course of the power density P over the distance x from the surface is steep, as depicted in **Figure 2.4**, in comparison to the course of the current density. Therefore, 86 % of the inducted power in the material to be heated flows within the penetration depth δ.

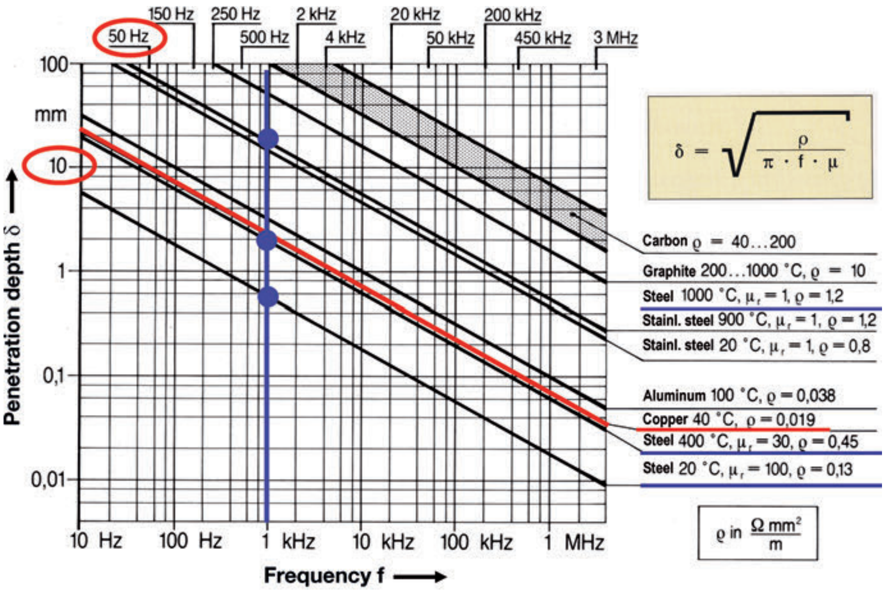

Figure 2.5: Penetration depth in dependence on frequency for different metals [7]

The penetration depths of common metals are shown in **Figure 2.5** in dependence on the frequency [7]. The strong influence of the electrical resistance ρ and also that of the magnetic conductivity μ can be recognized, as these apply to ferromagnetic steel in dependency on the temperature. At room temperature, this material has a permeability of 100, which drops to 30 at 400 °C and to 1 at the Curie point (768 °C). At a frequency of 200 Hz, the associated penetration depths are some 1.3 mm at 20 °C, for example, or 4 mm at 400 °C. At temperatures above the Curie point (and generally with non-magnetic steel), the penetration depths at 200 Hz are 35 to 40 mm, something like ten times as deep.

2.2. Induction furnace structural shapes

Induction furnaces can be differentiated into crucible and channel furnaces; their construction principles are illustrated in **Figure 2.6** [7].

In a channel furnace, the inductor flanged onto the furnace vessel can be regarded as a transformer, consisting of one or more primary coils with multiple turns around a closed ferromagnetic core and a short-circuited secondary winding. The current flowing through the inductor's primary coil generates an alternating electromagnetic field that primarily flows through the iron core. The single-winding secondary circuit represents the refractory lined inductor chan-

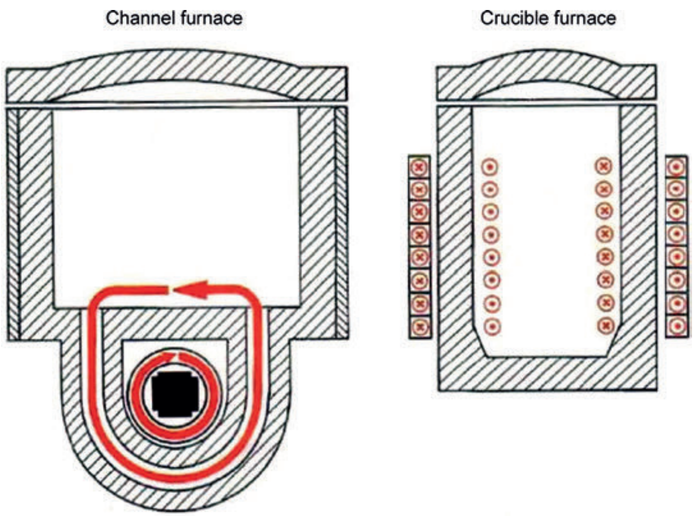

Figure 2.6: Principles of channel and crucible furnaces [7]

nel filled with liquid metal, into which a high, short-circuit current is induced. The thermal energy generated (Joule's heat) is transmitted from the inductor channel to the melt in the furnace vessel via the turbulent flows formed by the electromagnetic forces and thermal forces of lift. This principle of functionality delivers greater electrical efficiency as the main advantage of channel furnaces over induction crucible furnaces.

The latter work without an iron sheet core (which is why they are also known as coreless induction furnaces) under the electrical principle of an air-core transformer. The cylindrical induction coil runs around the refractory crucible for approx. 80 % of the crucible's height. As almost the whole furnace space is subject to the electromagnetic field, these furnaces can be operated with high specific power. A further benefit is that the melt experiences a strong inductive stirring in a crucible furnace; the drawback is their lower electrical efficiency.

2.3. Induction crucible furnaces

2.3.1. Electrical efficiency

The following equation applies to the electrical efficiency η_{el} of crucible furnaces

$$\eta_{el} = P_i / (P_i + P_v) \tag{2.3}$$

The greatest part of the electrical losses P_v occur in the furnace coil. The variable for the inducted power P_i is decisively dependent upon the ratio of charge diameter d to penetration depth δ. For scrap feed materials, charge diameter d is the diameter of the scrap pieces directly after charging, for melted metal it is the diameter of the furnace. The penetration depth δ is very small in comparison to the dimensions of the furnace. It changes greatly during the heating process due to the temperature dependence of the electrical conductivity and the permeability. Thus, an iron or steel melt has a penetration depth of approx. 80 mm at 50 Hz and of approx. 25 mm at 500 Hz, while cold-charged feed material has a penetration depth lower by a factor of 10 (see Figure 2.5).

Figure 2.7 shows the electrical efficiency factor for different metals and temperatures in dependence on the ratio d/δ [7]. For the induction crucible furnaces used in industry, d/δ is always greater than 6, thus in the high electrical efficiency range. The highest values of over 90 % are obtained when heating up cold ferromagnetic iron or steel. Once the Curie point has been passed at 768 °C, or where austenitic steel is concerned, the values drop to approx. 80 %. In the case of non-ferrous metals, the maximum electrical efficiency is far below as per Figure 2.7.

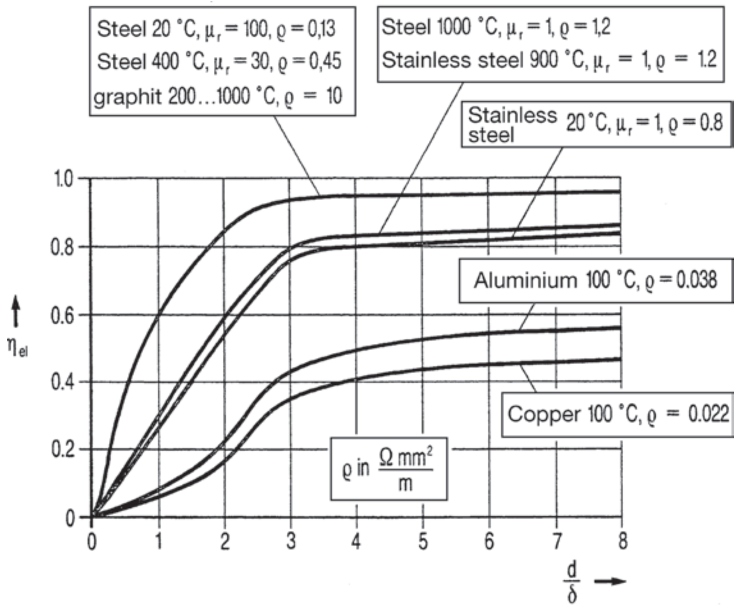

Figure 2.7: Electrical efficiency of an induction crucible furnace as a function of the ratio between feed stock diameter d to penetration depth δ for different materials [7]

2.3.2. Field line

The eddy currents in the material to be heated can only be approximately calculated by analytic processes. Thanks to the computer technology now available, numerical calculation methods are widely applied today. These obtain much more accurate results by simulating the crucible furnace in a two-dimensional, axial symmetrical model. The numerical methods used have progressed with regard to user-friendliness and speed to the extent that they have become the standard procedures for designing induction crucible furnaces [8]. Such calculation programs enable both the exterior electrical data of an induction furnace and also the field line inside the furnace to be exactly determined. As an example, **Figure 2.8a**) shows the field line in a medium frequency crucible furnace, consisting of the coil, magnetic yokes and melt.

The magnetic flux generated by the coil current partly runs through the melt, although the greatest part flows through the crucible wall between the coil and the melt. The exterior magnetic yokes form a magnetic return path and thereby guide the outer magnetic leakage field. They thereby prevent any heating of

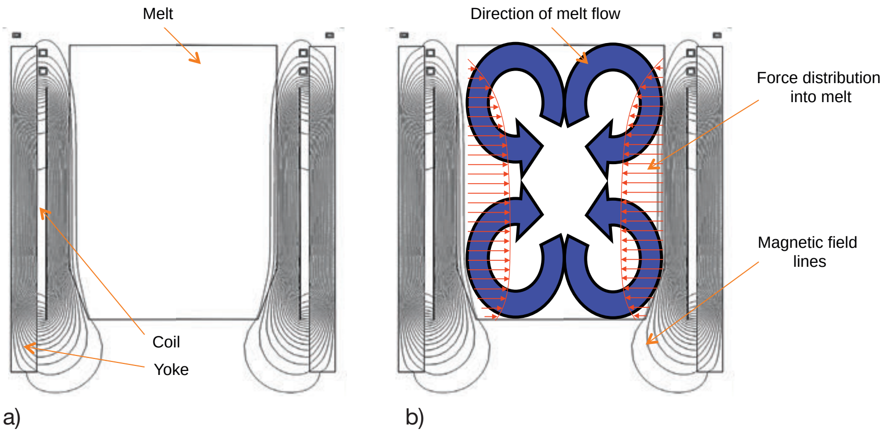

Figure 2.8: a): Field pattern of a medium frequency crucible furnace;
b): Power distribution and course of flow (Source: ABP Induction Systems GmbH)

the furnace structure and an inadmissibly high leakage field outside the furnace. It can be recognized from Figure 2.8a that the magnetic yokes protrude quite far out over the coil ends in order to catch the field leaking upwards and downwards. This is an important factor in the construction of industrial crucible furnaces, and is discussed in Chapter 3.1.2 “Coil and magnetic yokes”. The illustration also shows the high field density in the refractory wall, which leads to inductive heating of metal which has penetrated into the wall. This is described in more detail in Chapter 3.1.1 “Refractory Lining”.

2.3.3. Bath agitation

During inductive power transmission, electromagnetic forces are created from the interplay of the eddy currents induced into the melt and the magnetic induction (**Figure 2.8b**). These forces are responsible for the characteristic phenomenon of the bath meniscus and melt flow in induction crucible furnaces (**Figure 2.9**).

2.3.3.1 Bath superelevation

The electromagnetic forces basically run in a radial direction to the crucible axis and press the melt away from the crucible wall towards the center. Gravity works against these forces, so that a dome is formed on the bath surface. The dome $h_ü$ in the center axis has the following dependencies:

$$h_ü = K \cdot \frac{P_S}{\sqrt{f}} \quad (2.4)$$