Latest Developments in Recycling Production Residues Employing Coreless Induction Furnaces

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Abstract

One unique and well known feature of the coreless induction furnace is its pronounced metal bath movement, caused by the electromagnetic forces present. This bath movement, basically depending on the furnace power and operating frequency, is the reason for the good homogeneity of the melt regarding composition and temperature delivered by such furnace type.

On the other hand, this feature is widely used for stirring fine sized metallic scrap into the melt, eg. chips and swarf. This type of operation can be further optimized and tailored to the specific requirements by employing some new special circuits. Firstly, by choosing the multifrequency option, the furnace can be operated at different frequencies, depending on the filling level for example, in order to provide optimum stirring action at all stages of the melt cycle. Secondly, the power focus technology allows to concentrate the furnace power on specific regions of the induction coil, for example on the bottom of the coil to increase the furnace power with a partially filled furnace. Shifting the power to the top of the coil improves surface bath movement for improved stirring action at the end of the melt cycle.

The above techniques are demonstrated for the case of melting aluminium chips and foil bales, wet brass chips and for the recycling of ferroalloy fines. The latter is a brand new and challenging application since these fines incorporate a high amount of nonmetallics forming slags which have to be handled by the furnace and the process.

Finally, a new technology is presented, allowing to operate a coreless induction furnace at continuously adjustable frequency down to 30 Hz and with adjustable phase shift between two coil sections, thus offering unmatched freedom in selecting heating power and bath movement characteristics independently.

1 Introduction

Induction melting has become an increasingly widespread process in the foundry and semi-finished products industries given its technical and economic performance potential. Its basic advantages derive from the direct input of heat into the metal with almost no temperature overshoot and from the fact that the bath movement can be selectively controlled. These properties provide an accurate temperature and process control capability, low melting loss, reduced environmental and workplace pollution, and highly stable and precise analyses, all with high energy efficiency. The step to digitally controlled medium-frequency furnaces based on advanced frequency converter systems has brought a significant increase in power density and process engineering capabilities.

2 The coreless medium-frequency induction furnace

2.1 Design and operation

An advanced high-power induction melting system as shown in Fig. 1 is essentially made up of:

- the melting unit with furnace body and cradle,
- the electric power supply system with transformer, frequency converter and capacitor rack,
- the process control system with weigher, operator cabinet and melt processor as well as
- the peripheral equipment including water recooler, charger and dust collection system.

Fig. 1: Medium-frequency melting furnace

State-of-the-art furnaces with advanced frequency converter systems can be operated with a selectable frequency usually in the range between 60 and 1,000 Hz. In new coreless furnace projects, they have completely supplanted mains frequency installations due to their numerous advantages.

One major benefit, thanks to the higher frequency, is that the furnace can be started on solid charge material without any losses and it can be reliably operated with a power density which is a multiple of that of mains-frequency furnaces.

In an induction melting furnace the electromagnetic forces and the so-called eddies in the melt produce a meniscus on the one hand and pronounced bath movement on the other (Fig. 2). A common phenomenon in standard coreless induction furnaces consists in the emergence of counter-rotating vortex pairs which, in a high-powered furnace, may attain average flow velocities of 1-2 m/sec.

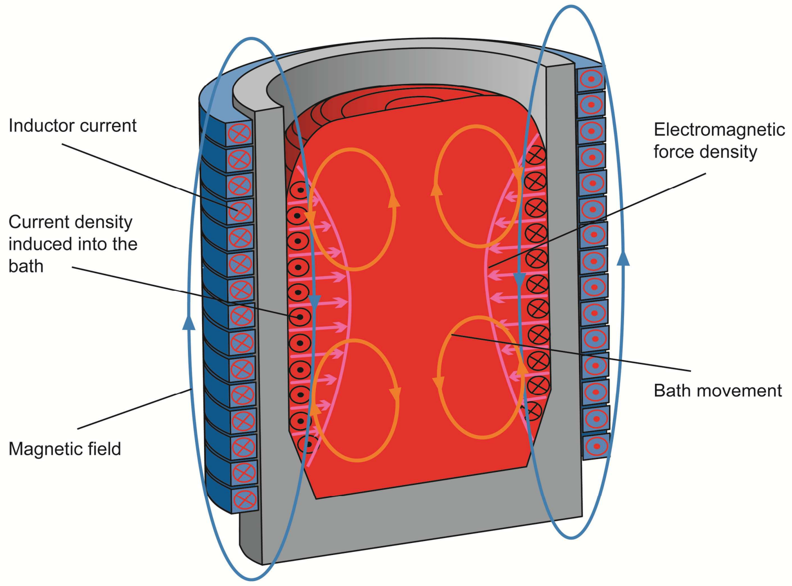


Fig. 2: Bath movement and meniscus

This bath movement is very important from a technological viewpoint since it facilitates an optimum melt homogenization and stir-down of constituents, thereby ensuring an optimum melt composition with excellent analysis and temperature accuracy at the same time.

The height of the meniscus and the intensity of the bath movement are a function of the a.c. operating frequency, the electrical power input, the furnace geometry and the metal level in the furnace. They can thus be selectively controlled.

Under this principle, the bath movement intensifies with rising electrical power input but diminishes as the frequency is raised. It should thus be noted that, for a given furnace power level, the heat input and intensity of the bath movement are interlinked. Therefore, a classic mains frequency three-phase stirring circuit used to be (and still is) employed in situations where a strong stirring action is required despite minimized heat input. However, this approach is associated with high costs. Modern converter technology now provides alternative solutions to this task which are described in the following sections.

2.2 Special circuitry

From a metallurgical point of view, the ideal induction melting process is one in which both the input of thermal power and the melt flow can be controlled to match given technological needs. In addition, the power input and bath movement should be mutually decoupled, i.e., the desired melt movement in the furnace should be adjustable independently of the respective power input. While it is no problem technologically to control the electric power and hence, the input of thermal energy into the melt, it takes very special circuit engineering to achieve control of the bath movement independently of this energy input.

Moreover, when discussing intense bath movement, it is necessary to distinguish between deep intermixing of the entire melt and mere surface flows, as shall be explained later.

Based on R&D advances achieved over the last few years, OTTO JUNKER has established its Power-Focus and Multi-Frequency technologies – two special circuit systems meeting the above requirements which have by now proven their merits in numerous installed furnace systems.

The Power-Focus technology permits an automatic or freely selectable concentration of power in that coil section (top or bottom) in which it is needed most. Thus, when the furnace is half empty, the power input can be focused in the lower crucible area in order to increase the energy input there. On the other hand, when the furnace is full one can direct more power into the top coil section so as to intensify the bath movement and hence, facilitate stir-down of the charge (e.g., metal chips).

The Multi-Frequency technology enables switching between different operating frequencies during the melting process. For example, an appropriate frequency of 250 Hz will be used to melt down the charge material. For the input of carburizing agents and alloying additives, the system is automatically switched to a lower frequency, e.g., 125 Hz. Practice has shown that this changeover to a reduced frequency can greatly accelerate the carbon pick-up in cast iron analysis adjustment (Fig. 3).

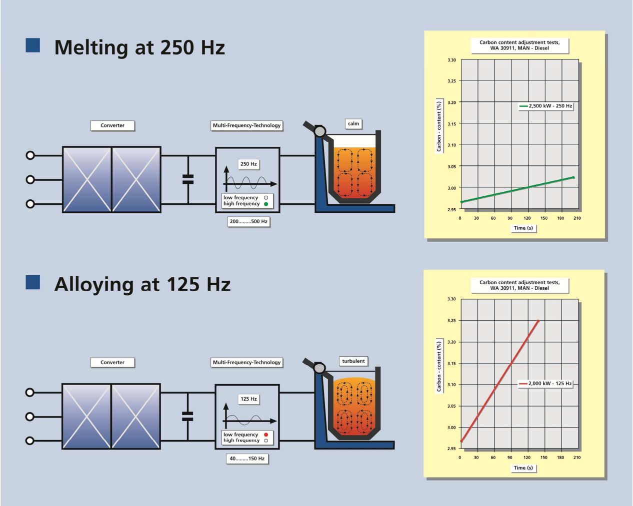


Fig. 3: Multi-Frequency system

It should also be mentioned that these two circuit configurations can be combined to amplify their respective effects.

These options are substantially expanded further by the latest developments utilizing the technical advantages of IGBT converter technology.

Apart from proven thyristor-based frequency converters, the successful development of special IGBT converters has come to play an increasingly important role in electrothermal processes. These systems involve the use of insulated gate bipolar transistors (IGBTs) instead of thyristors in the inverter.

The inverters and d. c. link circuit capacitors form one integral unit. This unit is suitable for use in a variety of circuit configurations. Typical examples are:

- independent inverters serving several furnaces
- multiple inverters for the coil sections of one furnace
- parallel connection for increased power
- series connection for increased voltage

Recent engineering advances have yielded IGBT converter systems, whose process technology applications are to be explained on the basis of an example [1].

The technical prerequisites for controlling the bath movement within a wide range are met by installing an IGBT converter with two separate inverters and a system ensuring a phase-shifted operation of the furnace coil sections. In the charge melt-down phase the furnace can thus be run at an appropriate nominal frequency of, e.g., 250 Hz and for increased bath agitation at low power the frequency can be steplessly controlled below 100 Hz. The amount of phase offset between the two coil sections is likewise adjustable to provide a selective control of the flow pattern (i.e., direction of rotation and velocity) in the central coil area of the furnace. This way, the region of maximum flow velocity can be moved into the interior of the molten metal bath and more effective intermixing of the entire melt will occur. The technical options available for influencing bath movement in a coreless induction furnace can be implemented and combined in manifold ways to address specific metallurgical tasks, as is summarized in Table 1.

Technical solution	Application examples
Multi-frequency technology Changeover, e.g., from 250/125 Hz	(Re)carburizing cast iron Alloying work
Power-Focus technology Concentration of power in the top or bottom coil area	Melting down chips at high throughput rates, e.g., aluminium chips
Low-frequency technology Operating frequency of 100 Hz or lower, down to below 30 Hz	Intense alloying work, e.g., for aluminium alloys Melting chips, melting down fine granular charge materials, metal powder, etc. (e.g., Cr, FeMn, FeSi) Producing surface reaction for cleaning Scrap processing by recycling and related value-adding treatment
Process-oriented IGBT technology Variable frequency (e.g., 250 Hz, stepless adjustment from 100 – 33 Hz) plus use of multiple coil sections with phase-shifted power supply	Same as low frequency technology Combination of high throughput and intense intermixing of the entire melt at low power. Pilot plants for determining optimum operating point in terms of heat input and flow velocity

Table 1: Influencing metal movement in a coreless furnace

2.3 Typical successful applications

The fundamental requirements for melting down small-sized charge materials can be summarized as follows: The focus is on minimum melting loss, high energy efficiency, reliability in operation, low environmental pollution and optimum efficiency, no matter whether aluminium foil, punchings, slab milling chips or machining chips of castings or ferroalloy fines need to be melted. Melting applications in the own company, so-called in-house recycling, also gains increasing significance.

The following describes just a few of the numerous successful applications of coreless medium-frequency induction furnaces for melting such types of charge material.

3 Recycling of fine-sized aluminium

3.1 Slab milling chips

In this case an induction furnace plant is to be used for the melting down of dry milling chips of the AlMg5 alloy of which large quantities are produced in the machining of continuously cast slabs. The specific surface area of the chips of 1.97 m²/kg is relatively small and the oxide content of slightly above 1 % is not really high.

Apart from low energy consumption and low melting losses the melting plant was expected to ensure high equipment availability and in particular a refractory lifetime of more than one year.

In order to reach this target the new medium-frequency furnace plant has been equipped with the Power Focus feature for selective power concentration and with variable operating frequency. In this way the power input can be focused on specific coil areas and the operating frequency is variable as a function of bath level and power input. Moreover, the structure-borne noise and thus the vibration of the furnace body is measured as well. If these values are too high the power input is reduced in order to protect the refractory lining.

The technical data of the furnace system used are as follows:

- Capacity 7.5 tonnes, rated power 2,600 kW, frequency 80 or 110 Hz selectable
- Chip input from storage bin via chute with controlled feed rate
- Automatic furnace control using the JOKS melt processor

The furnace is operated in such a way that metal is tapped down to a heel of 4.5 tonnes and then charging of the chips commences. For this the equipment parameters are set such as to ensure that the chips are stirred down swiftly and with low bath level the Power Focus system is used to concentrate power on the lower region of the coil. When the furnace is nearly full the frequency is reduced in order to maintain sufficiently strong bath movement for stirring-down the chips quickly.

3.2 Recycling of machining chips

A tremendous amount of chips and swarf with adhesive coolant is produced in the machining of car wheels made from ALSi9Mg alloy castings. After treatment in a centrifuge the chips still contain a residual amount of machining emulsion in the order of 1 to 2 %. The requirement was to perform melting operation in-house with melting losses below 1.5 % and with low energy consumption.

The system of choice was a medium-frequency melting furnace with a capacity of 3 tonnes and a power rating of 1,200 kW. The operating frequency was fixed at 110 to 150 Hz.

From a chip preparation system with storage bin and attached screw feeder the chips are fed to the melting furnace continuously. The chips enter the furnace through a swing-type lid with funnel-shaped opening (Fig. 4). Again, the furnace is started with a heel and the system is controlled such as to ensure quick stirring down of the chips without overfilling the furnace. The JOKS melt processor makes sure that any overheating of the melt beyond 780 °C is ruled out.

The furnace plant has been in operation with great success for several years, fully meeting the target.

Fig. 4: Induction furnace with chip conveyor

3.3 Recycling of aluminium foil

The plant in Italy – comprising a 5.5 tonne furnace with a power rating of 1,500 kW at 70 Hz – is used exclusively for the melting of baled foil of the 8006 alloy (pure aluminium with about 0.4 % of manganese).

The foil bales of 300 x 300 x 400 mm are slightly compressed and contain rolling oil residues of up to 2 %.

Fig. 5: The charge material: baled foil

The bales are charged into the furnace intermittently by belt conveyor, starting with a heel of about 50 %. Furnace power and charge input are controlled in such a way that the bales are embedded in the molten metal of the heel while the bath surface is permanently covered with bales.

Upon complete melting of the charge, the bath surface looks clean, bright and covered with just a thin oxide layer. Finally, the metal is tapped into a launder without prior dross skimming. The launder transfers the molten metal either to a gas-fired holding furnace or to an ingot mould.

As virtually no dross develops during the melting cycle the melting losses are negligible. Also, there is no need for cleaning the crucible wall, simply because there are no dross accretions.

The refractory lifetime is more than six months and the output is around 5,000 tonnes per lining campaign.

The results are most remarkable, the more so as the charge material has a very unfavourable surface area-to-volume ratio.

4 Melting of wet brass chips

Given the advantages of the coreless induction furnace (e.g., adjustable stirring action and higher throughput compared to a channel furnace of identical capacity), this furnace type is now increasingly preferred in brass chip recycling applications where it has all but replaced its channel-type counterpart. Still, even with a conventional coreless system, wet chips must typically be dried before being charged into the furnace. This drying step imposes significant extra cost. For this reason, an equipment concept was developed which allows wet brass chips to be recycled economically in industrial practice [2]. This made it necessary to integrate the chip charging system, furnace hood and off-gas management into the overall process, and to introduce a process control regime and automation system taking into account chip quality and throughput.

In metering the chips input it is essential that the oil residues are allowed to be pre-dried and burnt sufficiently before they reach the molten metal bath surface. The charging rate and furnace power are therefore matched and controlled such as to ensure that the furnace will neither overspill nor overheat due to a shortage of chips, causing a high degree of zinc evaporation. An optimum operating regime is established by continuous monitoring of the furnace weight and control of the furnace power input via the melt processor. The burning of oil or emulsion residues adhering to the chips causes high off-gas temperatures in the furnace hood which may exceed 1,000 °C by far. A ceramic lining of the furnace hood, plus water cooling of the first section of the extraction ductwork, avoid the formation of noxious substances and ensure a reliable operation of the filter system. Fig. 6 illustrates such a furnace.

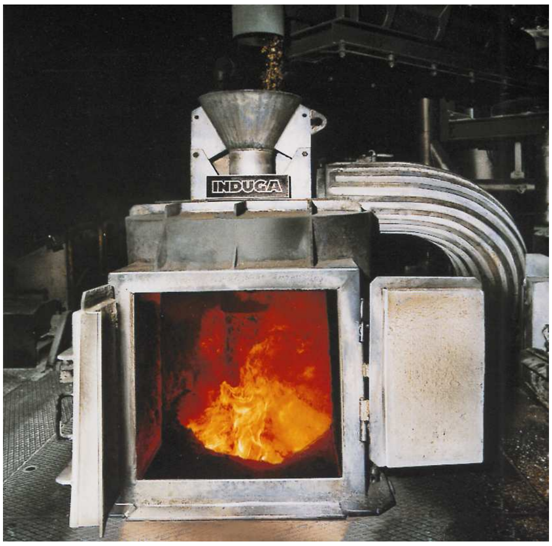


Fig. 6: Wet brass chip melting furnace

5 Recycling of ferroalloy fines

In breaking the ferroalloys – e.g., ferrosilicon or silicomanganese - obtained in pit-type electroslag remelting furnaces, a 0 - 13 mm grain size fraction (fines) is obtained in substantial amounts. However, this material cannot be usefully employed for metallurgical purposes. Similarly, it makes no sense either economically or technically to reintroduce it into the smelting process. As a result, these fines are typically disposed of as waste.

As far as recycling in a coreless induction furnace is concerned, the situation is complicated by two specific facts when compared to the remelting of chips and foils discussed above:

On the one hand, these alloys will not couple to the electric field at suitable operating frequencies while in a solid state, whereas in a liquid state they will. As a result, solid charge material cannot be melted down directly but only indirectly in a heel of molten metal. Furthermore, this implies that after a furnace relining, the refractory material needs to be sintered with a ferroalloy melt by a process referred to as liquid sintering.

On the other hand, these fines contain up to 15 % non-metallic components – mainly SiO_2 and Al_2O_3 in the case of ferrosilicon. Substantial amounts of slag will therefore form when such fines are melted down, and the viscosity of this slag is highly dependent on its composition and temperature. In the case of a coreless induction furnace conventionally rated (e.g., for cast iron or steel) in terms of a given capacity, power and frequency ratio there is a risk that the slag thus formed, which we shall initially assume to be of low viscosity here, will accumulate in the annular gap between the meniscus and crucible wall where it will float on the moving melt because it is of lower density than the metal. This molten slag will continue to accumulate and eventually begin to cover the entire bath. At this point at the latest, melting must be discontinued as the charge material will drop onto the slag, cooling it down and thus in turn increasing its viscosity. A process of this type will hence be characterized by frequent melting interruptions and laborious de-slagging. The situation described above applies to slag of an assumed low viscosity. In practice, however, the slag will not be of such low viscosity due to the composition of slag-forming agents present in the charge. As a result, the problem described above will be aggravated further.

In the light of these considerations and experience, a coreless furnace running at a low frequency and having a geometry promoting optimum bath movement was designed for the present task. Moreover, it was envisaged to add slag formers along with the charge material – based on the relevant phase diagrams – so as to reduce the melting temperature of the slag and hence, its viscosity at the operating temperature.

Through these measures it proved possible, starting out from a heel level of 50 %, to run a continuous melting process without any intermediate de-slagging until the furnace was filled to nominal capacity. The highly liquid slag could be poured off without any problems. This was facilitated by the intense bath movement, which was strong enough for the slag to be drawn down into the melt over and over again so as to retain the bath temperature. One indispensable requirement in a regime of this type is that the melting process must not be interrupted by any means, for the slag would otherwise rise up immediately in the absence of bath movement and would then form a liquid top seal that is impenetrable to the melt upon re-starting. De-slagging would then have to be carried out before continuing the melting cycle, although it had been the stated objective to avoid just that.

The furnace has a capacity of 3,000 kg relating to FeSi 75 and features a 250 Hz / 125 Hz multi-frequency capability. In the first trials it achieved a melting rate of over 2 tonnes/hour at a reduced power input. Fig. 7 shows a view into the crucible during the melting process. The charge material was drawn from a suitable hopper via a shaker chute.

Fig. 7: Melting down ferrosilicon fines

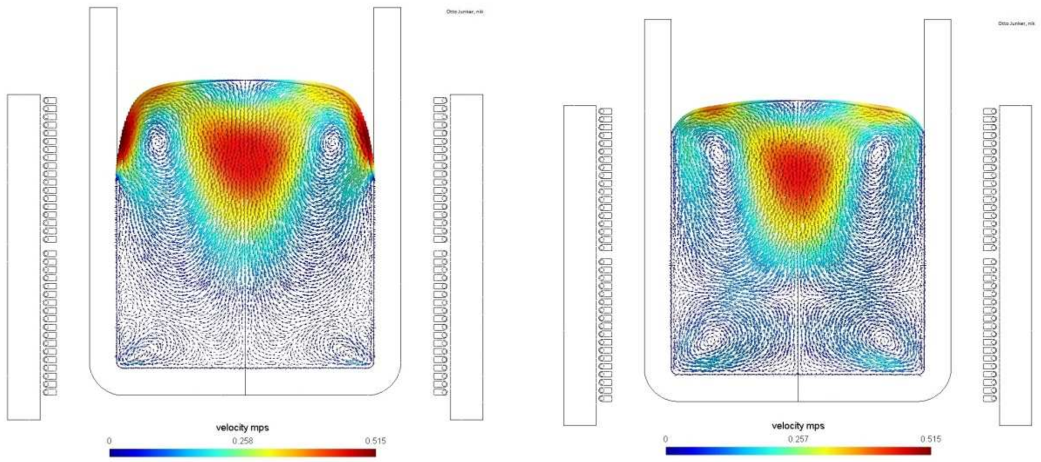
6 Melt refining system

In 2011, OTTO JUNKER was entrusted with the task of designing a coreless furnace capable of carrying out a melt refinement process involving plasma treatment. Once the furnace was filled to its nominal capacity, an active gas plasma was to be applied to the melt surface. The surface bath movement and hence, mass transfer was to be maximized while metal spillage was nevertheless to be avoided. At the same time, the temperature was to be kept as constant as possible over a treatment cycle of several hours, taking into account the heat input caused by the plasma burner.

Based on this specification, a furnace system with a crucible capacity of around 100 litres was designed, built and commissioned. Along with a conventional melting mode (230 Hz, 300 kW), this system provides a stirring mode at reduced heat input in which the frequency and power input are steplessly adjustable independently of each other The operating frequency ranges from 33 - 100 Hz, i.e., starting out from a bottom value below the mains frequency. Moreover, in stirring mode the two coil sections of this furnace system can be operated at two different phase angles in the manner known, e.g., from linear motors.

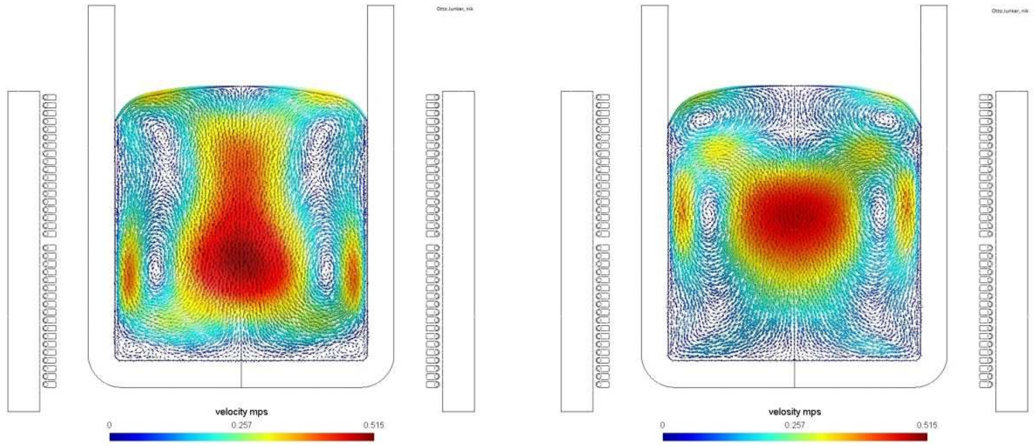
This design provides hitherto unknown flexibility as regards the independent control of its thermal power input and melt flow characteristics. An illustration of this is given in Figs. 8 a) – d) for the example of an aluminium melting operation. Fig. 8 illustrates the situation in melting mode at a power input of 128 kW and an operating frequency of 230 Hz. Figs. 8 c) – d) depict conditions at 28 kW / 24 Hz and a phase angle of 0°, +90° and -90°, respectively.

A comparison between Fig. 8 a) and Figs. 8 b) – d) makes the role of the operating frequency impressively clear. At 34 Hz, a mere 28 kW of power suffices to produce approximately the same flow velocity in the bath as at 230 Hz and 128 kW. Moreover, Figs. 8 b) – d) graphically illustrate the impact of the phase angle on bath movement.



a) 120 kW, 230 Hz, phi = 0

b) 28 kW, 34 Hz, phi = 0



c) 28 kW, 34 Hz, phi = +90 °

d) 28 kW, 34 Hz, phi = -90 °

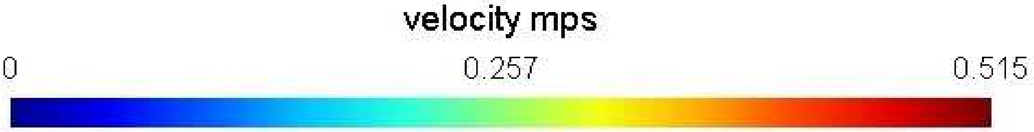


Fig. 8 a) – d): Impact of power, operating frequency and phase angle of currents in the coil sections on the intensity and patterns of bath movement

The furnace system fulfils its intended operating purpose in a fully satisfactory manner, yet the technology employed here opens up much wider perspectives. On the one hand, the low-frequency operating regime in conjunction with a phase shift enables engineers to design high-turbulence induction mixers providing ideal conditions for metal-slag reactions. At the same time, the increased magnetic penetration depth obtained at the low frequency supports the choice of a much thicker crucible wall compared to conventional coreless furnace, which is an indispensable requirement for such metallurgical tasks. Fields of application include, e.g., secondary metallurgical operations in steelmaking or copper refining steps in making semi-finished products. Moreover, this technology necessarily provides benefits when it comes to recycling fines, as described above.

Conclusion

Continuous improvements in induction furnace technology, especially in the field of frequency converter systems, have greatly expanded its range of process application options.

Accordingly, the induction furnace not merely represents an advanced and very powerful standard melting resource today – tailor-made designs are increasingly being employed to address specific metallurgical tasks. Summing up, it may be stated that the medium-frequency coreless furnace has evolved into a melting system meeting nearly universal requirements.

Literature

[1] TRAUZEDDEL, D.; SCHMITZ, W.: Giesserei 06/2012, S.26-30

[2] BEBBER, H.; SPITZ, W.: Furnaces International (01-02/2004), S.13-16