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Optimisation of the Thermal Process in Ladle Metallurgy in Terms of the Impact on Energy Consumption and the Environmental Burden During Steel Production

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Abstract: The paper focuses on reducing the energy intensity of ladle metallurgy as part of steel production and the associated reduction of pollutant emissions. It can be achieved by optimising the thermal work of metallurgical aggregates in terms of the impact on energy consumption and the environmental burden of steel production. It is about minimising the heat loss of liquid steel in the casting ladle throughout the entire process, from the melting equipment, through the extra-furnace processing, to the continuous casting of the steel.

Keywords: casting ladle, ladle furnace, extra-furnace processing, lining, energy consumption, ecological burden, steel production, continuous casting, high-temperature heating

1. Introduction

The ever-increasing demands for reducing energy costs directly related to reducing greenhouse gas emissions (mainly CO_2) are leading steel producers to develop new technologies to meet this requirement (Fredman and Saxen 1998).

The new greening measures are no longer directed only at the necessary air purification, where the technology and filtration from the 1990s are becoming obsolete. Now comes the dramatic greening of production processes and operations from pig iron to steel production (Besta et al. 2020). The last few years have been marked by a comprehensive and drastic greening of individual large pollution sources and by dusting off individual production halls, which often contain up to several dozen small pollution sources. However, metallurgical production will never match the purity of medicine producers.

Ensuring the top quality of produced steel, along with the high productivity and low operating costs of the steelworks in question, is currently only possible with modern secondary metallurgy and continuous casting processes. Secondary (ladle) metallurgy is technologically related to the steel melting units of primary metallurgy. It takes over part of the technological operations performed in melting aggregates, includes difficult or impossible operations to perform in melting aggregates, and provides conditions for the subsequent casting of steel (Tvardek et al. 2008).

Current technologies of ladle metallurgy and continuous steel casting place high demands on the refractory lining of casting ladles. With continuous casting and the expansion of secondary metallurgy, the ladle has ceased to be a simple means of transporting steel from the primary aggregate to the casting machine. It has become a reactor in which the metallurgical process continues after separation from the furnace unit. Part of the technological steps originally belonging to the primary aggregate was transferred to the casting ladle, and new ones were added, which allowed increasing the share of production of steels with unique properties and higher utilisation values, expanding the number of steel grades, shortening the production cycle and making production more economical (Tvardek et al. 2008). In particular, steel casting ladles play an essential role in steel production, and their optimisation requires an understanding of the thermal state of each specific process step (Fredman and Saxen 1998).

With the introduction of continuous casting and the spread of ladle metallurgy, the casting ladle ceased to be a mere means of transporting steel from the primary unit to the casting machine but became a reactor for the subsequent metallurgical process after separation from the furnace unit. Part of the technology was transferred from primary aggregates to them, and new ones were added to increase the share of production of steels with unique properties and higher utilisation values, to expand the number of steel grades, shorten the production cycle and make production more economical.

Casting ladles are used not only for steel transfer but also for ladle metallurgy processes with liquid steel, with subsequent casting into the transfer ladle on individual continuous casting machines (Jančař et al. 2008). These are conical-shaped steel vessels lined with refractory materials that resist the high temperatures of hot steel and the corrosive action of aggressive slag and are capable of retaining large amounts of heat (Jančař et al. 2008). The inside of the ladle is made of a heat-resistant ceramic working layer. The outer side of the ladle consists of a circular steel shell with evaporation holes, a support system, and an arched bottom with openings for casting and argonisation. The individual ladles are numbered on the ladle shell for identification.

The wall and bottom of the ladle are made of magnesite-dolomite fittings. The impact area and the slag zone of the casting ladle are lined with magnesite-carbon mouldings.

During its working cycle, which is determined by the technological nodes formed by the individual production units of the steelworks, the casting ladle can be in the following operating states:

- high-temperature heating,
- the tapping point,
- transporting a ladle filled with steel,
- the processing of steel in the ladle furnace,
- casting,
- natural cooling in the air or under cover.

The actual working cycle of the ladle is preceded by its preparation for the operation, which includes lining, drying of the insulating and protective layer, preheating of the working layer of the lining, fitting of the ladle with a spout and a special block for argon blowing and reheating to the desired ladle temperature (Jančař et al. 2008).

Like all basic materials that come into contact with molten steel, dolomite linings require preheating before they can be used. The technology of drying or preheating the new lining of the casting ladle according to a modified drying curve was introduced. The modification consists in a more gradual temperature rise, where 1000°C is reached only after about 12 hours of drying, compared to the original curve, where 1000°C was reached after 7 hours. This modification means more gentle thermal stress on the refractory material of the casting ladle lining and a considerable saving of natural gas required for preheating the new ladle lining.

The benefit of the new curve for preheating the casting ladle lining before the ladle is put into operation is a considerable saving in natural gas consumption, which in our case is about 370 m^3. Another advantage of this method of preheating the casting ladle before its use is the more gentle heating of the refractory material, whose thermal stress is less intense in the initial phase of the first preheating and thus does not cause temperature "shocks" of the dolomite mouldings.

The ideal temperature the new lining should reach before the first firing into the ladle is 1000-1100°C. Regarding 'dry' lining, the ladle must be heated to at least 700°C in the vertical position. The ladle can only be flipped to a horizontal position once this temperature has been reached. The first preheating should take 18-24 hours to achieve sufficient heat accumulation in the lining.

Short cycle times are the most effective way to keep the ladle in a heated state. If the time difference between the pouring of the ladle and the subsequent tapping is longer than 30 minutes and the ladle is not fitted with a lid, it must undergo interstitial heating. Another possibility is using refractory bricks, and refractory concrete without C content are potential candidates for reducing the energy consumption of ladles (Santos et al. 2020).

Determining the optimum thermal condition of each process step will lead to an environmentally friendly solution when considering the application of suitable refractory and insulating materials (Liu et al. 2014).

The aim of the article is to propose procedures for minimising the heat loss of liquid steel in the casting ladle in the entire technological flow, which will positively reduce energy consumption and environmental impact in steel production.

2. Optimisation of the thermal work of the casting ladle

Analytical (Zimmer et al. 2008) and numerical models (Li et al. 2015) have been investigated by various authors to understand the thermal states (Uchida 2010) and the energy transfer (Ogata et al. 2015) during the operating cycle of the casting ladle. The objective of those approaches are the physical properties of the process and the energy consumption for different refractory linings. Furthermore, appropriate modelling of the steel ladle can also indicate the temperature of the metal casing, which affects its service life and quality (Xia and Ahokainen 2001).

The ladle circulation system has become an essential part of the steelworks control system, monitoring the movement of casting ladles in the steelworks and recording all the conditions each casting ladle goes through. The thermal state assessment model and the steel temperature change model work together with this system. Functions have also been developed to control the high-temperature heating of the ladles (Tvardek et al. 2009). The preheating function of the ladle linings has undergone some changes in the new conditions of the steelworks, which are due to the long residence time of the liquid steel in the ladle and, thus the high enthalpy of the lining at the end of casting. Modern ladle shrouds can serve tens of heats with the help of upgraded alumina-graphite composites, structural design and coating technology (Zhang et al. 2019).

The above-mentioned technologies of information systems used in the field of ladle metallurgy, together with the introduction of an insulating layer in the lining of the casting ladle and the reduction of the number of ladles in use, lead to the optimisation of the thermal work of the casting ladle at the steelworks. In particular, the incorporation of an insulating layer in the casting ladles lining together with the covering of the casting ladle with a lid results in better use of the heat of the liquid steel accumulated in the lining of the casting ladle from the previous melting, which leads to a reduction in the consumption of natural gas for preheating the casting ladle and a reduction in electricity consumption for heating the steel in the ladle furnace.

Within the automated control system of the steelworks, technological sub-models are used to monitor the casting ladles' actual circulation and determine the thermal state of their linings throughout the entire working cycle. Based on operational monitoring of the ladle circulation, technological sections of the steel production process were specified, algorithms for dealing with changes in the thermal state of the ladle lining were derived, and sets of constants of technological models were calculated (Jančar et al. 2008). It should be emphasised that the constants are individual and must be determined separately for each type of ladle lining.

In the first phase of modernising the steelworks control system, the operational measurement of the casting ladles at the steelworks was carried out on non-insulated ladles. The reason for this was the inclusion of the existing type of casting ladle lining in the steelworks' information system. The operational measurement of the fully insulated casting ladle is currently underway. In the first case, the results of the operational measurements were used to introduce a model for controlling the high-temperature heating of the casting ladles. The second case is the operational testing of the casting ladle lining with the incorporation of a high-performance insulating material into the ladle wall.

In both cases, the result was a reduction in energy consumption in steel production and extra-furnace processing.

The operational measurement of the casting ladles is carried out as follows:

Preparation for measurement:

- installing thermocouples between the individual layers of the lining when forming the wall of the casting ladle,
- installing the thermobox on the outer surface of the steel casing,
- placing the measuring control panel in the insulated thermobox,
- connecting thermocouples to the measuring control panel.

The actual measurement process during the working cycle of the ladle:

- during the drying and preheating of the ladle before the first melting,
- in the section from the tapping to the end of casting (full ladle),
- in the section from the end of the casting to the subsequent tapping (empty ladle),
- when cooling for a long time, covered by a lid,
- during heating after a long cooling period covered by a lid.

The measured data were then used to calculate the enthalpy of the ladle in each technological section and determine the parameters of the above-mentioned technological models.

Technological models in the field of ladle metallurgy are based on algorithms dealing with identifying the thermal state of ladle linings during their operation in the steelworks. Algorithms work in the background based on automatic or manual input into the control system. Their task is to monitor the thermal condition of the ladle linings during their closed working cycles. The monitoring is carried out using the values of the specific enthalpy of the ladle lining and the duration of the individual thermal engineering operations. It creates a background for using a custom model in specific operational situations (Jančar et al. 2005).

The general scheme of the control system of the casting ladle circulation, including the interconnection of the individual technological models, is shown in Figure 1.

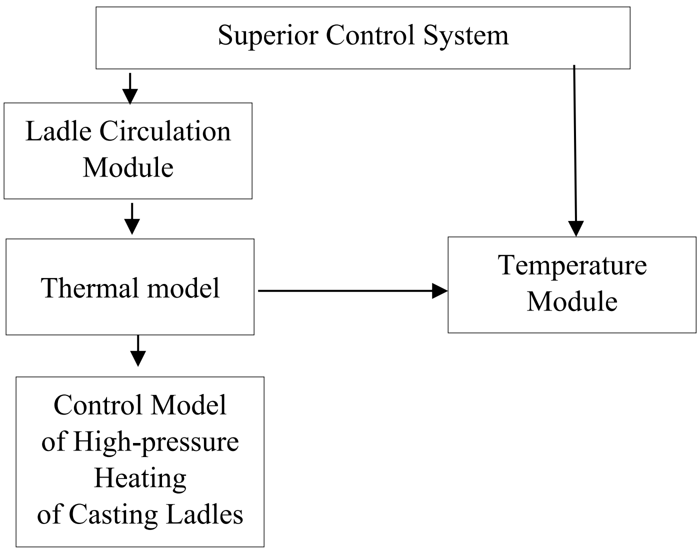

Fig. 1. General diagram of the casting ladle circulation control system

Figure 1 shows a schematic representation of the ladle circulation control system, including supporting models. All models work against the background of the steelworks' master control system.

The casting ladle circulation module monitors the individual states of the casting ladles during their working cycle, including each operation's start and end time. These data are inputs to a model for calculating the thermal state of casting ladles (thermal model), which calculates the enthalpy of the ladle at each moment of its working cycle (Jančar et al. 2005). The outputs of the thermal model (enthalpies) together with the data of the steelwork's master control system (steel temperatures, type of steel produced and other operational data) are also inputs to the thermal model, which, among other things, deals with the heat loss of steel through the ladle lining. The thermal model is also used to control the high-temperature heating of the casting ladle (Jančař et al. 2008).

3. Methods

Based on the analysis of experimental measurements of the ladle's surface and internal temperatures and simultaneous measurements of the steel temperature during all full ladle operations, model constants were developed to evaluate the thermal state of the ladle. These constants were included in the individual algorithms of the enthalpy calculation model (Jančar et al. 2008b).

The model contains several program modules, each of which describes the enthalpy of the ladle in a given working state (Taddeo 2005). The individual modules build on each other, i.e., the enthalpy calculated within one module is the input (initial) value for the next ladle state (module).

The enthalpy of the lining was chosen as the most suitable parameter for defining the thermal state of the ladle. This quantity is a function of time and is generally given by this equation (Tvardek et al. 2008):

$$I\ (\tau) = \int_V t(x,y,z,\tau) \cdot c_p(t) \cdot \rho_v \cdot dV \text{ (J)} \tag{1}$$

where:
$I(\tau)$ – the enthalpy of the lining at a given time τ, (J),
$t(x,y,z,\tau)$ – wall temperature at x,y,z and time τ, (K),
$c_p(t)$ – specific heat capacity depending on temperature t, ($J \cdot kg^{-1} \cdot K^{-1}$),
V – the volume of the ladle lining, (m^3),
ρ_v – the volumetric mass of the ladle wall, ($kg \cdot m^{-3}$).

As c_p is a function of temperature, the quantity $I(\tau)$ also characterises the change in the accumulation properties of the lining as a function of its temperature. The algorithm for determining the thermal state of the ladle is thus reduced to the determination (calculation) of the enthalpy of the lining (Tvardek et al. 2008).

The temperature change of the steel in the ladle is determined from the heat balance of the liquid steel and is given by the sum of the partial temperature changes of the steel for a certain period. These partial changes express the contribution of the individual heat input and consumption items to the overall change in steel temperature (Trulleyová 2010).

One of the heat loss items is the heat loss of steel through the ladle lining, which is influenced by the type of casting ladle lining and the operating and technological conditions of the steelworks.

The heat loss through the lining is determined as a time-dependent integral value for the entire lining of the casting ladle. The temperature drop of the steel caused by heat losses through the lining in the specified period is determined by the relation (Hašek et al. 2004):

$$\Delta t_{vyzd} = \frac{Q_{vyzd}}{m_{oc^*}\, c_{oc}} \text{ (°C)} \qquad (2)$$

where:
Q_{vyzd} – the heat loss through the lining (J) over the selected period,
m_{oc} – the weight of steel in the ladle (kg),
c_{oc} – specific heat capacity of steel ($J \cdot kg^{-1} \cdot K^{-1}$).

The model constants for calculating the heat loss of steel through the casting ladle lining were also determined based on operational measurements of the temperature profile of the ladle lining (Framchi 1993).

4. Reducing Energy Consumption in Steel Production

The objective was achieved primarily by incorporating an insulating layer into the ladle lining and an emphasis on covering the ladle with a lid wherever possible. Verifying its effect is not only on reducing natural gas consumption during the high-pressure heating of ladles but also on reducing electricity consumption for heating steel in the ladle furnace.

In order to determine the extent of the savings resulting from the implementation of all the measures mentioned above leading to the optimisation of the operation of the casting ladles, a comparison of the data measured during the operational measurements with the data obtained from the regular operation of the existing casting ladles was carried out.

As can be seen from the above facts, the practical use of the model to manage the preheating of the casting ladle linings, reduce the number of ladles in circulation and the use of insulation for casting ladles, together with compliance with the use of ladle lids wherever possible, is a clear benefit. Since the purchase price of the technology, including insulation, is several times higher than the standard equipment, it was necessary to determine the savings that could be achieved using this new technology. The savings consist of reduced consumption of natural gas for high-temperature heating of the ladles and electricity for heating the steel in the ladle furnace.

The calculated savings for fuel gas are given per hour and for electricity per tonne of steel produced (see Table 1). These are calculated savings without the cost of the ladle insulation.

Table 1. Comparison of energy consumption

Type of energy	Unit	Ladles after optimisation	Other ladles	Savings	
				Specific	Annual
Natural gas	m^3/h	85.0	107.3	22.3	0.74 mil.
Elect. energy	kWh/t	35.6	40.2	4.6	9.2 mil.

As already mentioned, the preheating of the casting ladles during the operational tests to date has resulted in significant savings in fuel gas and electricity. This energy saving has a direct impact on the reduction of CO_2 emissions.

5. Reducing the Environmental Burden of Steel Production

Gaseous fuels are composed of several substances (gases) that contain carbon in addition to CO_2 (CO, CH_4, C_2H_6, C_3H_8 and other hydrocarbons). Other substances contained in the fuel (H_2, H_2S) also contribute to oxidation, but they do not affect the formation of CO_2. The combustion of the substances involved in the production of CO_2 follows these chemical equations (Tvardek et al. 2008):

$$CO + 0.5O_2 \rightarrow CO_2 \tag{3}$$
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4}$$
$$C_2H_6 + 3.5O \rightarrow 2CO_2 + 3H_2O \tag{5}$$
$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \tag{6}$$
$$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O \tag{7}$$
$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \tag{8}$$
$$C_3H_6 + 4.5O_2 \rightarrow 3CO_2 + 3H_2O \tag{9}$$
$$C_nH_m + 3.8O_2 \rightarrow 2.6CO_2 + 2.4H_2O \tag{10}$$

Equation (3) shows that 1 m^3 of CO produces 1 m^3 of CO_2. Equation (4) shows that 1 m^3 of CH_4 produces 1 m^3 of CO_2. However, in equation (5), we see that 1 m^3 of C_2H_6 produces twice the amount of CO_2. In equation (6), it is already three times the amount, and so on to equation (10), where we see that 2.6 times CO_2 is produced from 1 m^3 of unsaturated hydrocarbons C_nH_m.

Calculations of the amount of CO_2 produced by the combustion of gaseous fuel must consider the conditions under which oxidation occurs. It is, therefore, necessary to know the pressure and temperature. In our case, the gas consumption is already converted to standard conditions.

The **volume of CO_2** in the flue gas, which is produced by the combustion of 1 m^3 of fuel, is calculated from the relation (Tvardek et al. 2009):

$$V_{CO_2} = \frac{CO+CH_4+2*C_2H_6+3*C_3H_8+4*C_4H_{10}+2*C_2H_4+3*C_3H_6+2.6*C_nH_m+CO_2}{100} \left(\frac{m^3}{m^3 fuel}\right) \quad (11)$$

CO – the amount of carbon monoxide in the gaseous fuel (%),
CH_4 – the amount of methane in the gaseous fuel (%),
$C2H_6$ – the amount of ethane in the gaseous fuel (%),
C_3H_8 – the amount of propane in the gaseous fuel (%),
C_4H_{10} – the amount of butane in gaseous fuel (%),
C_2H_4 – the amount of ethylene in the gaseous fuel (%),
C_3H_6 – the amount of propylene in gaseous fuel (%),
C_nH_m – the amount of unsaturated hydrocarbons in the gaseous fuel (%),
CO_2 – the amount of carbon dioxide in gaseous fuel (%).

To convert the volume of carbon dioxide in the flue gas to mass, we use the formula (Tvardek et al. 2009):

$$m_{CO_2} = V_{CO_2} \cdot \rho_{CO_2} \ (\mathrm{kg \cdot m^{-3}\ fuel}) \quad (12)$$

V_{CO2} – the volume of carbon dioxide in the flue gas ($m^3 \cdot m^{-3}$ fuel),
ρ_{CO2} – density of carbon dioxide 1.9642 ($kg \cdot m^{-3}$).

To calculate the amount of CO_2 emissions that would result from burning the amount of fuel saved we use (Jančař et al. 2005):

$$M_{CO_2} = m_{CO_2} \cdot U \cdot AO \quad (13)$$

m_{CO2} – the mass of carbon dioxide in the flue gas ($kg \cdot m^{-3}$ fuel),
U – hourly natural gas savings ($m^3 \cdot h^{-1}$),
AO – annual operation of high-pressure heating equipment (h).

Calculation of the natural gas CO_2 emission reductions for the high-pressure heating of ladles

Calculation of natural gas flue gas quantity for high-pressure heating of casting ladles:

Table 2. Chemical composition of natural gas expressed as a percentage (data used from company sources):

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_nH_m	CO_2	O_2	N_2
%	97.155	1.288	0.405	0.066	0.8	0.159	0.5	0.816

The volume of CO_2 in the flue gas, which we calculate from relation (11), is 1.04 $m^3 \cdot m^{-3}$ of fuel for the conditions of the steelworks. Therefore, the mass of CO_2 in the flue gas is 2.03 $kg \cdot m^{-3}$ of fuel.

The amount of CO_2 emissions that would result from burning the saved fuel is:

$$(2.03 \cdot 22.3 \cdot 33{,}229)/1000 = 1{,}504.24 \text{ tonnes per year.}$$

For the individual operational measurements, including the calculated average, the reduction in CO_2 emissions due to natural gas savings is shown in Table 3.

Table 3. Reduction of CO_2 emissions due to lower consumption of natural gas for high-temperature heating of casting ladles

Saving natural gas (m^3/year)	Emission CO_2 (t/year)
741,007.8	1,504.24

Calculation of solid fuel emissions

A further reduction in CO_2 emissions will occur by saving on the electricity needed to heat the steel in the ladle furnace. However, this emission reduction is indirect, as the amount of greenhouse gas produced is not reduced directly but occurs in the power plant by burning less coal to produce the electricity it consumes.

In order to calculate CO_2 emissions, it is necessary to know the amount of coal burned for power generation and its composition, especially carbon content. CO_2 emissions from the combustion of hard coal follow the equation:

$$C + O_2 \rightarrow CO_2 \tag{14}$$

As the equation shows, to burn 12 kilograms of carbon, we need 22.4 m^3 of oxygen to produce 22.4 m^3 of CO_2.

After adjustment, we get the equation for calculating the CO_2 emissions:

$$V_{CO_2} = \frac{22.4}{12} \cdot \frac{C}{100} \tag{15}$$

V_{CO2} – the volume of carbon dioxide in the flue gas ($m^3 \cdot kg^{-1}$ fuel),
C – carbon content of hard coal (%).

The combustion of coal with 75.9% carbon content, according to equation (15), produces 1.417 $m^3 \cdot kg^{-1}$ of CO_2 emissions. If we burn 0.449 kg of hard coal to produce 1 kWh of electricity, then this would result in a 9.2 million kWh reduction of electricity consumption (see Table 1), saving 4,131 tonnes of hard coal (0.449 · 9.2 · 106), resulting in a potential reduction of 5,854 tonnes of CO_2 per year (1.417 · 4,131 · 106).

The above analysis shows that the average annual saving of natural gas for the high-temperature heating of the casting ladles is about 741,000 $m^{3,}$ and the resulting reduction in the amount of CO_2 emissions is about 1,504 t. On the other hand, in the case of the electricity saving for heating steel in the furnace, the annual saving is about 9 million kWh, and the resulting reduction in the amount of CO_2 emissions is about 5,854 t. It means that the total reduction of CO_2 due to the reduction of electricity is about 7,358 t.

6. Conclusions

A prerequisite for maintaining the competitiveness of steel companies on a global scale is the continuous reduction of not only material but also the energy and environmental demands of steel production.

This paper focused on optimising the thermal process of metallurgical aggregates in terms of the impact on energy consumption and the associated reduction of pollutant emissions in steel production. The aim was to achieve minimum heat loss of the liquid steel in the casting ladle throughout the entire process, from the melting equipment, through the extra-furnace processing to the continuous casting of the steel.

Today's steel production technologies are characterised by constant pressure to produce high-quality steels, which cannot be done without state-of-the-art equipment in furnace aggregates, ladle metallurgy and steel casting. However, with all this machinery, there are increasing demands not only on the service life of their linings due to the higher temperatures caused by the more extended stay of the steel in the individual aggregates, especially in the casting basins, but also higher pressure on environmentally friendly processes. It can be achieved by optimising the heating of the metallurgical aggregate linings, using a quality insulating layer in the aggregate lining and, last but not least, by optimising the number of casting ladles in circulation.

The mentioned optimisation steps were verified by operational experiments, based on the results of which these recommendations were created, which were applied in the actual conditions of the given enterprise with positive impacts on energy consumption and environmental burden in steel production.

The result is not only a considerable saving of heating media with a direct impact on the reduction of CO_2 emissions, but by properly observing the covering of the ladle with a lid as soon as possible after casting the steel, together with the incorporation of an insulating layer in the ladle lining, the heat loss of the steel through the lining is minimised, which will mean, on the one hand, a more uniform temperature gradient of the ladle – transfer ladle and, on the other hand, the possibility of a permanent reduction of the tapping temperature with a consequent increase in the service life not only of the lining of the furnace aggregates but also of the casting ladles (less thermal "shocks" during tapping).

Metallurgical companies are aware of the dangers of climate change. They are gradually reducing their carbon footprint and taking a responsible approach to protecting the environment. Metallurgical companies strive to maximise the recycling and recovery of by-products and waste generated in their production processes. There is currently no commercially viable technology for producing steel without a carbon footprint. The metallurgical industry is innovating its products, intending to direct steel products off the production lines as much as possible into industries that contribute to reducing the carbon footprint.

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