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ENERGY EFFICIENCY IMPROVEMENT IN STEELMAKING PROCESSES BY APPLYING CFD METHODS

Key words

Metallurgy, efficiency, CFD methods.

Abstract

The development of the main sectors of the steelmaking industry is followed directly by the need to increase energy consumption for technological processes, which directly impact the amount of greenhouse gas emissions being emitted into the environment as carbon dioxide, which is a by-product in the combustion of fuels for energy generation purposes, being carried out in power plants supplying steelworks with electricity. Thus, it seems legitimate to search for new production technologies, which combine both, a high quality of steel products together with reduction of production costs, while increasing energy efficiency. A solution for this can be application of computational fluid dynamics (CFD). The article presents capability analysis to determine whether a selected steel-making process is capable of improving its efficiency by

applying optimization-based technological parameter specifications with the use of computer software, working based on CFD methods, in the production cycle.

Introduction

Currently observed global development of production technologies for manufacturing modern materials (among which the most significant business sectors are chemical, energy, metallurgy, and directly related to them, industrial divisions, (e.g., automotive, aviation, electronics and medical branches) sets high quality requirements in the field of applied solutions in terms of design and technology. These requirements have become the major cause for undertaking actions to improve the existing production technologies and to search for new and innovative solutions. Performing detailed analysis of a given technological process may lead to a situation in which inefficient sources of this chain are determined, so this allows for their elimination or improvement. Technological processes employed in particular industrial branches are based on controlled chemical reactions and physical phenomena. The application of relatively easily accessible and at the moment high-performance computational units can replace labour intensive analyzes of the process algorithm and revise technological procedures utilized therein by applying properly designed numerical simulations. An example of such solutions can be computational fluid dynamics (CFD).

CFD methods, due to the high reliability level of the obtained results, have very wide applicability in all branches of the industry, as well as for test designs and simulation studies on the expansion of fires and the introduction of contaminants into the environment.

In commercial metallurgical processes, CFD can be applied to model both the metal manufacturing technologies as well as for its further processing. In this case, the intended aim for using numerical methods is to obtain cast products free of inhomogeneity and defects. In order to obtain a high quality product, it is required to carry out analysis of all phenomena accompanying the ongoing metallurgical processes, to enter the process into the computer system, and to process the data numerically. The results obtained from computations are employed as input parameters in the process, which is also constantly monitored and subjected to any required adjustments posed by the obtained numerical computations.

Fundamentally, CFD software programs are based on utilizing the Navier-Stokes equations to describe flows of incompressible fluids [1]. These equations are subjected to discretization by means of the finite element method, the boundary element method, the finite difference method, meshfree models, finite-volume models, or control-volume models, also known as control areas. Thanks to discretization and the numerical solution of partial differential equations describing the analysed process of fluid flows, it is possible to determine approximately the distribution of velocity, pressure, temperature, as well as, other parameters. CFD software programs currently used enables one to perform flow analysis, regarding their viscosity and compressibility, multiphase nature and chemical reactions that occur therein (including combustion, flows through porous structures and flows, in which as the flow agent is used Newtonian or non-Newtonian fluid).

To describe the process being modelled with CFD numerical methods, following data are used:

- Object – as a part of the analysed real unit isolated from the environment;
- Input and output – streams of information (on mass and energy), which connect the object with the environment;
- The (physical, chemical, thermodynamic, or other) process subject to the analysis of real matter subject to change over time; and,
- Technological process – object described quantitatively by using variables.

The dependence between these variables, input and output and time, are described in a mathematical model. Model development is based on two approaches:

- A theoretical one – based on the knowledge on the laws governing phenomena accompanying the process; and,
- A phenomenological one – set on the basis of observations (measurements) of causes and effects.

Numerical modelling enables, among other things, precise determination of the duration of physicochemical processes associated with melting steel. Such knowledge allows one to optimize the consumption of input materials, media (gases) and energy. For example, among software applications using CFD methods in metallurgical processes, the following can be used: ANSYS FLUENT, CFX, MAGMA, PROCAST,VULCAN,NOVAFLOW, PAM-CAST, and SIMTEC.

Accurate and fast analysis of the process (using numerical tools) allows one to achieve the intended purpose of the production through the possibility of permanent control of process parameters and their possible correction.

Since the production objective will be achieved resulting in a product with high quality parameters, it is simultaneously possible to increase the efficiency of the process in terms of decreasing technological expenditures, energy efficiency, and related adverse environmental side-effects. Energy efficiency improvements of the process with the related reduction of CO2 emitted into the atmosphere are the key requirements laid down in Art. 13 of the Law on energy efficiency of 15 April 2011 [2]. Actions that should be undertaken by end user of electricity in order to improve energy efficiency are specified in Art. 17

paragraph 1 point 3 letter of the cited Act, as directly related with modernization of equipment and systems used in industrial processes.

1. Research methodology and analysis of the obtained results

This research study presents capabilities of using the CFD methods to optimize energy consumption at a ladle furnace station during steel production processes in one of steel plants located on the territory of the Republic of Poland. Based on the analysis of several dozen heat record cards for tested steel grades, weights of alloying elements were determined. Specific weight groups of additives were distinguished, including mean values that were used in numerical simulations. These model tests allowed for outlining contour maps visualizing alloy addition concentrations for selected values of mixing time (an example in Figure 1a). Significantly, the set up degree of chemical homogenization in the analysed ladle furnace can be reached. Figure 1b indicates exemplary changes in concentrations of alloy addition elements. The dimensionless concentration are defined as follows:

$$C_b = (C_t - C_0)/(C_\infty - C_0) \tag{1}$$

where

C_t, C_0, C_∞ – are alloy concentrations at the given time *t*, at the beginning of the process and at the end of the process respectively.

After approximately 125 seconds from the time of adding an alloy element, at certain conditions (including the weight of the added element and argon flow rate), total chemical homogenization of the metal bath occurs.

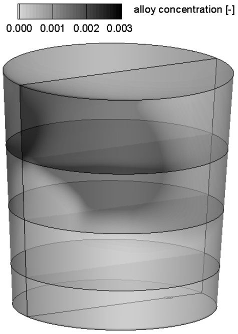

Fig. 1a. Contour maps of alloy addition concentration at a selected mixing time (argon concentration = 200 l/min alloy element addition = 45 kg) t = 20 s

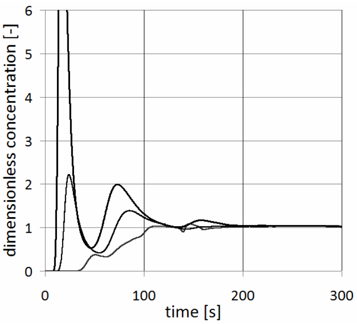

Fig. 1b. Concentration changes of alloy addition in selected measurement points P1, P2 and P3 for the test case with the addition element weight of 45kg and argon flow rate of 200 l/min

To perform more accurate analysis of the process of mixing alloy addition in the ladle furnace, at computational domain can defined measurement points at which alloy addition concentration is being measured. In the analysed example, there are three measuring points that are located in areas of varying degrees of agitation. If in the measurement point at 95 percent of bath's homogenization is reached, then the condition to complete time measurement process is complied. Therefore, based on series of numerical simulations, it is possible to determine the relationship between the mixing time of an additional element and the rate of argon flow or the weight of alloy addition. By analysing these relationships, the time required to achieve the assumed degree of chemical homogenization can be unambiguously determined, being dependent on the weight of addition element and the flow rate of gas being inserted. To illustrate this, the predicted time needed to attain chemical homogenization of bath after adding 140kg of an additional element was adopted, depending on the weight of addition element being inserted or on the gas flow rate (see Tables 1 and 2).

Table 1. Forecasted time of chemical bath homogenization after introducing an addition element weighting 140 kg into ladle furnace, depending on the argon flow rate at 95% homogenization of chemical bath in selected area of monitoring

Flow intensity [Ndm^3/min.]	Forecasted homogenization time t [s]
200	160
300	134
400	122
500	107

Table 2. Forecasted time of chemical bath homogenization for argon concentration of 200 l/min, depending on the mass of alloy addition at 95% homogenization of chemical bath in selected area of monitoring

The mass of alloy addition, [kg]	Forecasted homogenization time t [s]
45	128
140	160
230	173
500	203

In industrial practice of steel manufacturing facilities, when the alloy addition is being introduced, it is common to insert gas, which is blown through the furnace for a much longer time that it is specified in recommendations of numerical modelling. It is true that the objective of this process is to remove non-metallic inclusions from liquid steel; however, this process should be performed at minimum gas flow rates, which can be also determined by using numerical tests.

Analysis of a few dozen of heat record cards during the production cycle of a selected steel grade allowed us to determine the average time of blowing inert argon into the process, after the additional element was added, which lasts 5–8 minutes; whereas, the average flow rate of argon was in the range of 200–400 Ndm^3/min. Comparison of times needed to achieve the assumed degree of homogenization with the actual time of blowing inert argon allowed the estimation of the amount of gas being consumed (Tables 3 and 4).

Table 3. Theoretical consumption of argon computed based on numerical simulations

		Flow intensity, Ndm^3/min.			
		200	300	400	500
Time	Time, s	Consumption, dm^3			
	160	533.3	-	-	-
	134	-	670.0	-	-
	122	-	-	813.3	-
	107	-	-	-	891.7

Table 4. Actual consumption of argon calculated based on heat record cards

		Flow intensity, Ndm^3/min.			
		200	300	400	500
Time	Time, s	Consumption, dm^3			
	300	1000	1500	2000	2500
	390	1300	1950	2600	3250
	480	1600	2400	3200	4000

A similar situation is evident in the case of heating steel using electricity. After the alloy is introduced into the bath, a drop in temperature is observed. This requires the heating of the process. Electrodes are employed in the process of heating, which lasts few minutes. The length of time depends on the temperature of the metal bath being measured and on technical process specification and smelter's professional experience. Whereas, numerical simulations allow for very precise determination of the time needed for heating the metal, which depends on the weight, product's grade, or temperature of the additional element being introduced, and consequently, this can be converted into measurable benefits in the form of energy savings.

Figure 2a demonstrates an exemplary temperature contour map, and Figure 2b illustrates temperature changes during the metal bath, as a function of time, under specific conditions. Performed simulations showed that, after approx. 110 seconds from the time of inserting the alloy under specific conditions (addition mass and argon flow rate), total thermal homogenization of the metal bath occurs.

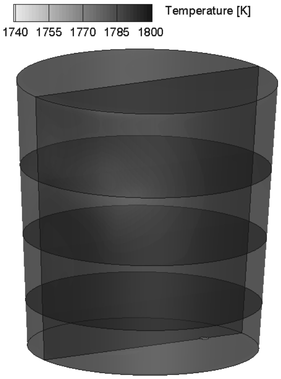

Fig. 2a. Contour maps of temperature for selected argon time values (argon concentration = 200 L/min, alloy addition = 45 kg), t = 20 s

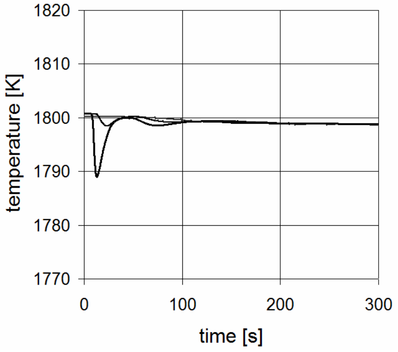

Fig. 2b. Change in temperature of the liquid steel in selected measurement points P1, P2 and P3 for addition size of 45 kg and argon flow rate of 200 l/min

Table 5 demonstrates the minimum, maximum, and average electricity consumption by the ladle furnace in the analysed steel plant before and after applying the CFD method. Comparing the data with numerical simulation results, as in the case of determining the degree of homogenization, the size of over-consumption of electricity can be estimated. The performed numerical simulations for the test ladle furnace have indicated that, after a 20-minute shutdown of the furnace, during which significant temperature stratification occurs, less than 3-minute gas mixing ensures complete thermal homogenization of cast metal.

Table 5. Values of electricity consumption during steel manufacturing processes at the working-stand of ladle furnace for the ladle furnace before and after applying the CFD methods

	Electricity consumption before using CFD method in [MWh]	Electricity consumption after using CFD method in [MWh]
Min value.	4.32	3.6
Max value.	8.74	7.6
The weighted arithmetic mean	6.41	5.34

To determine the amount of CO_2 emission caused by consumption of electricity needed for technological processes in the ladle furnace before and after the CFD methods are applied, a reference indicator for CO_2 emissions per unit defined by the National Centre for Emissions Balancing and Management in Warsaw, which equals to: 0.812 Mg CO_2/MWh [3]. This indicator is the basis for determining baseline levels, and then, for calculating the size of emissions that was avoided or reduced due to the implementation of such applications, which lead to the limitation, reduction, or avoidance of CO_2 emissions from conventional sources using fossil fuels.

Table 6 summarizes the minimum, maximum, and average CO_2 emissions released into the natural environment due to electricity consumption for the operating ladle furnace in the analysed steel plant before CFD methods are employed. The results of environmental improvements are also listed in the table.

Table 6. Summary of minimum, maximum and average CO_2 emission released into the atmosphere due to the consumption of electricity by using a ladle furnace in the analysed steel-making plant before applying CFD methods with the received environmental effect

	CO_2 emission volume due to electricity consumption before CFD method application of [Mg]	CO_2 emission volume due to electricity consumption after CFD method application of [Mg]	Ecological effect gained due to a decrease of CO_2 emissions released into the atmosphere [%]
Min value	3.508	2.923	16.667
Max value	7.097	6.171	13.043
		the arithmetic mean	16.693

Conclusions

Research results presented in this article indicate that the application of computational fluid dynamics in metallurgical processes affects the following:

- The production efficiency and quality improvement for a product without defects;
- A visible cost reduction in mass production (as a result of reduced energy and gas consumption) leading to minimizing total production losses; and,
- Energy efficiency improvement in the steel-making process, while reducing the emission of carbon dioxide into the natural environment due to the combustion of hard coal in power plants supplying energy for the end user.

References

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Poprawa efektywności energetycznej procesów stalowniczych poprzez zastosowanie metod CFD

Słowa kluczowe

Hutnictwo, efektywność, metody CFD.

Streszczenie

Rozwój głównych gałęzi przemysłu hutniczego związany jest bezpośrednio ze zwiększeniem zapotrzebowania na energię ze strony prowadzonych procesów technologicznych, co ostatecznie skutkuje zwiększeniem ilości gazów cieplarnianych emitowanych do środowiska w postaci dwutlenku węgla – jako produktu spalania paliw energetycznych w elektrociepłowniach zaopatrujących huty w energię elektryczną. Słuszne zatem wydaje się poszukiwanie nowych technologii produkcji łączących zarówno wysoką jakość produkowanego wyrobu stalowniczego wraz z obniżeniem kosztów, przy jednoczesnym zwiększeniu efektywności energetycznej. Przykładem może być zastosowanie metod numerycznej mechaniki płynów (ang. *Computational Fluid Dynamics*, CFD). Artykuł przedstawia analizę możliwości poprawy efektywności wybranego procesu stalowniczego poprzez zastosowanie w cyklu produkcyjnym wytycznych wynikających z optymalizacji parametrów technologicznych, z wykorzystaniem oprogramowania komputerowego pracującego w oparciu o metody CFD.