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The designing of gases energy recovery in high-temperature process

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Abstract

This paper deals with the combined process of production of ferrosilicon and power in an arc resistance furnace. Selected results of mathematical modeling of key installation units are presented. To this end, mathematical modeling, balance-measuring methods and practical experience were used. From among the many activities required to implement the project, the author chose ones associated with: the furnace hearth, after-combustion area, flue gases and recuperator channel as well as the recovery system and flow characteristics of the device. The presented modeling study forms part of a new design method termed the integration of computational processes.

Keywords: Combined energochemical cycles, Resistance-arc furnace, Computational Fluid Dynamics, Process Gases

1. Introduction

Considerable amounts of energy are lost in high temperature processes. The biggest source of lost energy is process gases enthalpy. It is possible to use this enthalpy through coupling the melting process with an energy recovery installation. The effect obtained is a combination of the melting process and gasification as well as the conversion of chemical into electrical energy. Beside the main product, some gaseous components and heat from cooling processes are obtained, which can potentially be used in an effective way. The advantage of combining these processes arises due to a much decreased tar content in the process gas (when compared to gasification processes conducted separately) [1]. That is mainly caused by the high process temperature, which accelerates the thermal decomposition of tars. Conversion of the process gas obtained in high temperature processes does not require precipitation of condensates before enthalpy recovery.

The combination of metallurgical and energy processes requires significant structural changes in the following system: furnace—flue gases channel—recovery system—flue gases cleaning installation. The very structure of the modified device allows for better planning of the device subsystems, which in turn creates potentially better possibilities for control of many process parameters. Furnace installation efficiency depends mainly on temperature excess in the process [2, 3]. In the arc chamber created around the electrode, the temperature exceeds 3,000°C [4, 5], which is necessary for the decomposition process SiO_2=SiO+0.5 O_2 to run. In the furnace, the energy for the reduction process comes mainly from Joule heat (about 55%), electric arc heating (approximately 20%), and combustion or co-combustion of the reducer, which is coal, coke and woodchips. For many years, coke has been used as the reducer in those furnaces, as it is characterized by an appreciably smaller amount of volatile components and a higher reactivity (due to higher porosity and larger inner surface of pores), yet increased resistivity, and thus worse properties in terms of adjustability of heating zones in the furnace [4]. The use of coal or biomass with a high content of volatile components (above 30% mass.) positively influences the metallurgical process, on the other hand, but leads to the escape of a significant part of reducing gases to the area over a heterogeneous reactions zone. The co-generative process can

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be used to increase energy efficiency [6–8].

The general assumptions of the simplified energy recovery process are simple and described in many publications [9]. There is, however, a discrepancy between the schematic energy chart and the industrial application of the installation. This is due to the fact that before implementation of the installation, in addition to determining the general energy assumptions [8], many details of the furnace devices system, furnace area, engine room and dedusting unit must be defined. Technological conditions limit the possible parameters of energy cycle parameters. This requires, inter alia, technological expertise and analyses of flow, combustion, heat transfer and mass transfer at various stages of the project. Process balance examination is also important [6] because without expertise of multi-phase flow processes or particular individual processes, it is not possible to effectively plan a functional system of that kind.

The aim of the work is to present selected results of the computational analysis of the flow systems within the furnace, recovery system and the gas turbine installation. The study also addresses the effects of constructional changes made to important stages in the smelting process. Many similar components make up an integrated model of the device. The model allows for the introduction of recovery systems. The presented results were obtained using computational fluid dynamics (CFD). Computational integration of the process necessitates the application of optimal and efficient computational codes, methods of numerical discretization of elements of the analyzed devices as well as suitable measurement methods.

2. Device description

Fig. 1 shows a simplified outline of the combined process of electricity production and ferrosilicon smelting FeSi75. The most important new element of technology is the cap of the furnace (4) providing a controlled flow of gas and safe supply of raw materials and electric energy through material inlets and electrodes (6). Air from above the taphole (1) and air sucked in through the technological windows from the furnace area is supplied to the area under the cap (2) by periodical lifting of the curtain (3). The air from the area above the taphole can also be supplied by a separate flue gas channel connected to the flue gases system. The flow characteristics of the channel connecting the flue gases collector with the flue gases channel should be properly shaped. The curtains are controlling elements with highly non-linear flow characteristics. They can be treated as binary elements with a minimum opening area, which arises from furnace thermal safety requirements. The main stream of after- combustion air is supplied through the after-combustion air nozzles and raw material distributors placed in the upper part of the cap (4). Air pressure drops in the after-combustion air system are surmounted by a fan (5). If, for whatever reason, flue gases cannot be carried away through the recuperator channel, process gases leave the furnace cap through the bypass channel (7) which is opened by regulating shutters (9). Then, through a draft diverter (10) gases are carried away through the suction fan (11) to the dedusting unit. During normal operation of the energy production installation, gases are removed to the recuperator channel (8), behind which they join the bypass channel. The cooling of the gases in the recuperator channel involves flow resistance reduction and thereby reduced demand for energy. In industrial application, energy systems consisting of several boilers and one turbine are used.

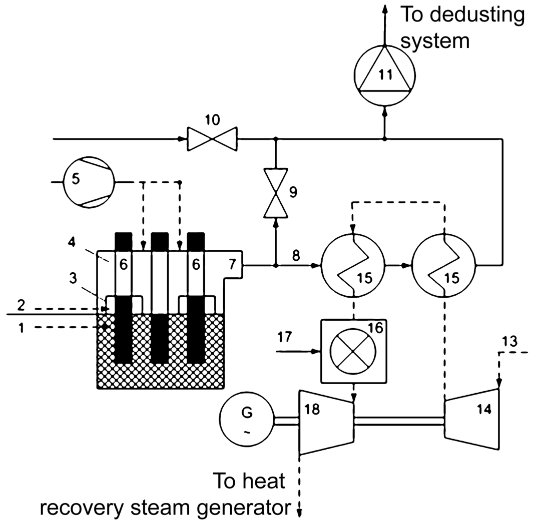

Figure 1: Simplified schematic of the main part of the process

The power installation is based on a single-shaft gas turbine. An air stream from the environment (13), after leaving the compressor (14), is supplied to the tubes of a U - type recuperator (15) where it is heated to nominal parameters (700 °C, 12 bar). Brayton cycle efficiency of the gas turbine depends heavily on the temperature of the gas supplied to the expander. For this reason, in the combustion chamber (16) with the addition of natural gas from the gas supply system (17) the working agent is heated to the optimal thermodynamic parameters. When flue gases leave the outlet of the turbine expander (18) they go to the recovery system, where depending on the need, heat, coolness or electric energy can be produced with the use of a low temperature cycle. The thermodynamic param-

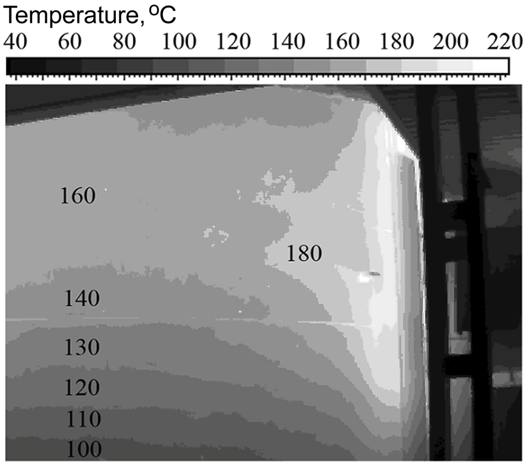

Figure 2: Infrared photo of furnace bed

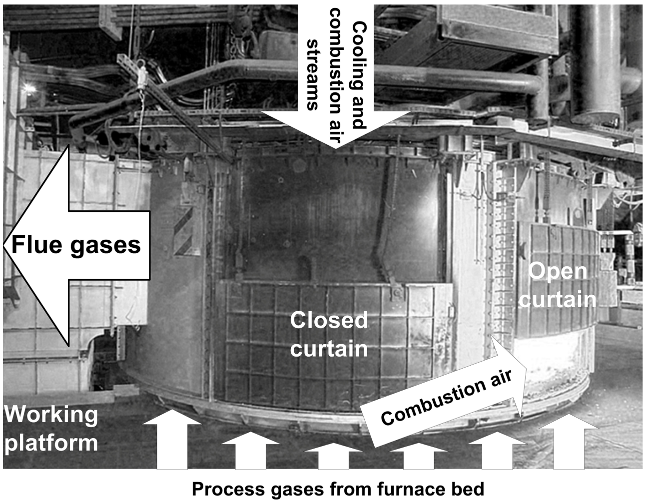

Figure 3: Furnace cap

eters of the turbine circulating agent are selected in accordance with the typical data given by the manufacturer. Therefore, appropriate and stable operation of the furnace is a relevant factor.

3. Selected results

3.1. Process gases

The computations done for the bed are relevant to understanding the relationship between the FeSi smelting process and gases creation, thermal zones and interactions between the process and hot gases. Increasing energy recovery from process gases necessitates the after-combustion of gases leaving the heterogeneous reduction area. From the point of view of installation cost, it is important that the gases are after-combusted in the area over the bed of the furnace, namely, in the area of the cap. This leads to an increase in temperature over the taphole, and disturbs the ferrosilicon smelting process. Physical and chemical interactions in the bed furnace were described by Machulec [4], whose non-stoichiometric model is used to determine the composition of the gases carried away from the area of the furnace hearth.

The balance of substance and energy in furnace is supplemented with an analysis of heat loss. The analyzes performed were based on well-known hearth surface temperature distributions in existing devices. Fig. 2 shows a schematic of the temperature tests of the furnace hearth shell with a capacity of 8.8 MWe conducted by the author.

3.2. Furnace cap

Fig. 3 shows a photo of the furnace cap. The device imposes severe limitations on ferrosilicon smelting, which is usually carried out in devices with the flue gases channel placed at an appreciable distance from the reaction bed—termed an ‘open system’.

According to the process assumptions, complete and perfect combustion should take place in the area of the cap. Due to the significant amount of energy in the process coming indirectly from electrical processes, the material limitations and heterogeneity of gas streams in the furnace area, and the air/gas equivalence ratio for the after-combustion of process gases, the air fuel equivalence ratio is $\lambda = 3.5$.

Opening the technological windows causes pressure and temperature disturbances as well as a cyclic excess of oxidizer, which in turn results in a temperature decrease in the gases leaving the cap and pulsating pressure. With closed shutters, the full heat load of the working area is obtained. In the case of electric arc radiation loss to cap, it may lead to local overheating and destruction of the furnace.

Anticipation of heat zones and programming of the optimal arrangement in the device is possible through effects simulation using CFD methods. Fig. 4 presents the computational methods of fluid mechanics used and the mathematical specification of the combustion reaction. Some of the results of gas temperature modeling in the area of the cap are presented in Fig. 4.

As can be seen, the temperature field is highly heterogeneous. This simulation allows us to anticipate the areas with the highest heat load and determine suitable protection of the furnace as well as supply of a precisely defined amount of air to the area under the cap in order to stabilize the highest possible temperature—in terms of material and technology—of the gases leaving the furnace. Due to the heat load (resistance) of the recuperator ma-

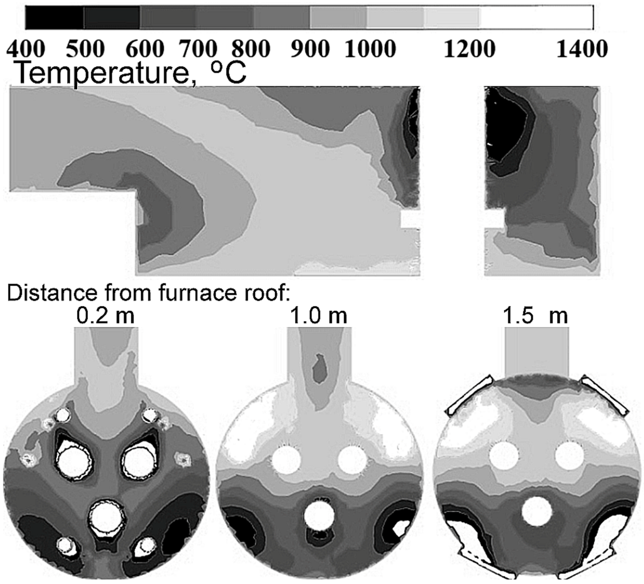

Figure 4: Temperature gradients inside the furnace cap. Results of calculations for total air fuel equivalence ratio $\lambda = 3.5$

terials, the temperature of gases leaving the cap cannot exceed 950 °C.

3.3. Recuperator and the flue gas channel

Combusted gases leaving the cap should give back the excess of their enthalpy to the compressed air side of heat exchanger. A U-type recuperator [10, 11] was selected for use in the installation. The information required to determine the optimal selection of materials and auxiliary equipment for energy recovery are: arrangement of the heat exchanger tubes, analysis of the effectiveness of gases flow, heat loads on the walls of the recuperator, and pressure drop characteristics of the recuperator for flow on the hot (flue gases) and cold (compressed air) side. To a large extent, correct assumption of the temperature zones in the gaseous area of air and flue gases, and in the material enables one to reduce device costs and to make effective use of the device heating surfaces. Fig. 5 illustrates the spatial distribution of the furnace in relation to the recuperators.

Computation variants allowed us to determine temperature zones of the exchanger and to select materials. Fig. 6 shows selected results in respect of temperatures in the flue gases channel.

The necessity to assess the possibility of temperature stabilization in the channels of furnaces working in the system–two furnaces–two recuperators–one gas turbine, developed during the experiment. In the case of a sudden decrease in the temperature of gases carried away from one of the furnaces, there is an asymmetry of heat load of the turbine and compressed air system. Compensation of this asymmetry with the use of an additional external control system is not recommended, as it limits the range of stable control of the whole installation. Thus, the possibility of process stabilization through connection of the flue gases channels was examined. In the examined solution, it was assumed that part of the gases in the channels will mix gas-dynamically.

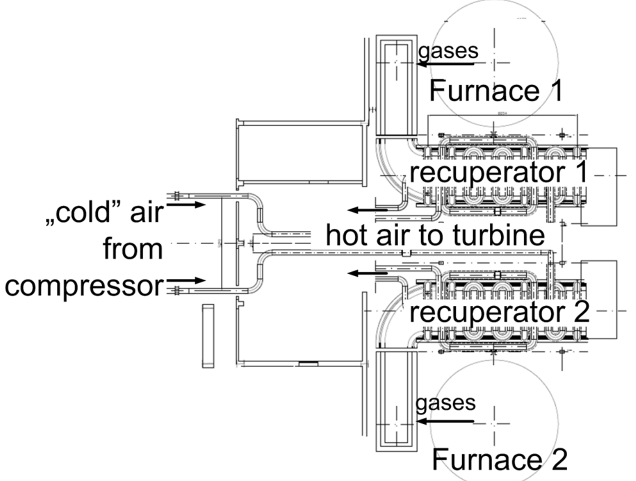

Figure 5: Spatial distribution of the furnace in relationto the recuperators. Top view [error in chart above - "cold"]

It would also have a stabilizing effect on gas pressure in both recuperator channels. One of the analysis variants is presented in Fig. 7a.

Fig. 7b. shows analyzes results of flue gases channels cooperation to identify the possibility of temperature stabilization in the channel, in the case of cooperation between the two furnaces. Typical furnace parameters (power, amount of raw material) were assumed, in one of them, however, a process-related gas temperature decrease occurred. As can be seen, the proposed connection of channels causes a small (c. 30%) averaging of the flue gases temperatures.

Based on the results of the calculations, an equation defining the local pressure loss factor ζ of process gases flow through the recuperator was formulated as a function of the air fuel equivalence ratio supplied under the cap λ and Reynolds number Re of gases supplied to the flue gas channel, calculated for the hydraulic diameter of the channel inlet window. This equation can be written as a correlating relation in the form of:

$$\zeta = 205 + 8.71\lambda + 52.88 \cdot 10^9 Re^{-2} \tag{1}$$

It is one of the key results of the modeling and forms the basis for the design of the dedusting system and the

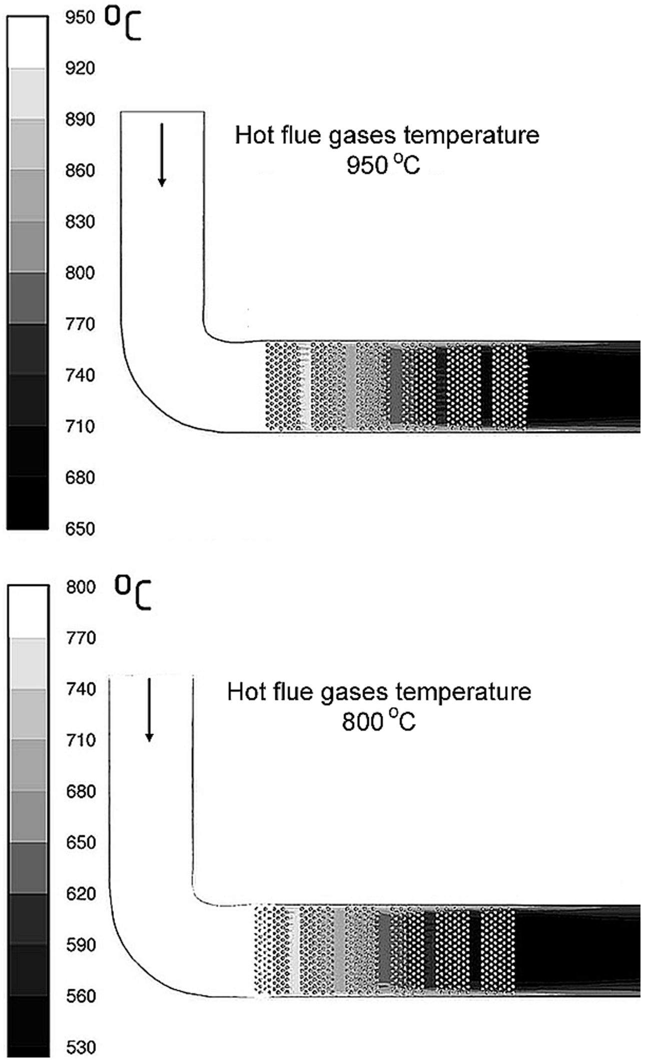

Figure 6: Temperature gradients inside the recuperator channel. Average velocity of gases at channel inlet: 10 m/s

gas path. The result obtained informs the selection of adjusting/control elements and fans cooperating with the recovery system. Knowledge of the flow characteristics components of the entire gas system allows us to select fans appropriately and thus to recover more energy.

4. Undesirable solution-related effects

Flue gases path insulation results in higher temperatures and therefore higher requirements on fire-proof and construction materials. Gas flow control/adjustment leads to higher gas pressure gradients and directional gas flow through the granular bed in the reduction zone and, thus, to the washing of SiO out from the reaction area and to a smaller yield of silicon from the process. Ongoing exothermic reaction

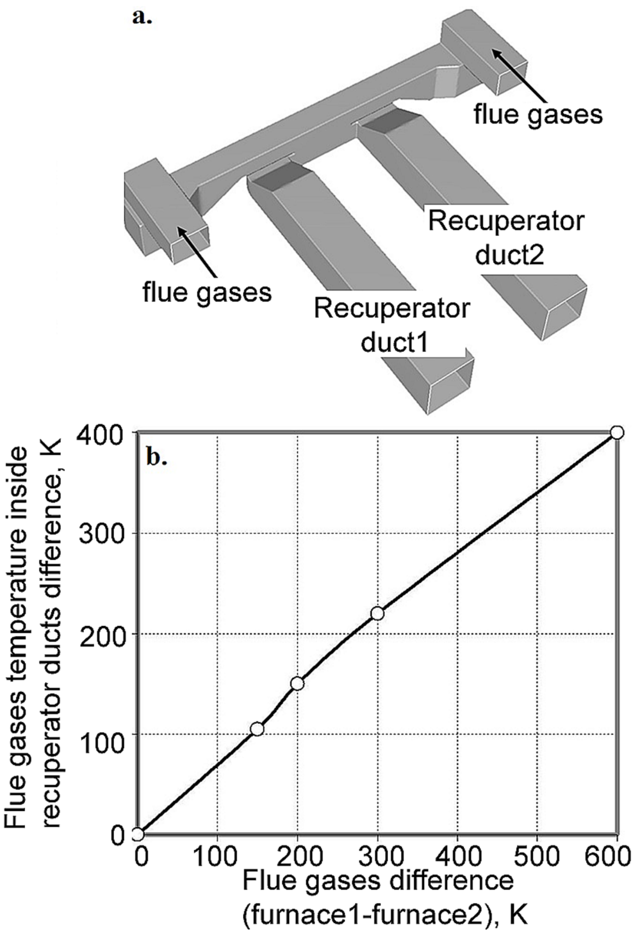

Figure 7: Mixing intensity analysis in coupled flue gases channels; a. channels configuration, b. mixing intensity in the form of temperature differences in the flue gases channel

$$SiO + 1/2\,O_2 \rightarrow SiO_2 - 206.534\ \text{kJ/mol} \qquad (2)$$

becomes a significant element of the cap balance. It is however possible to decrease/limit the process of gases washing out through suitable shaping of the pressures field under the cap.

A furnace equipped with a semi-open cap has much greater thermal dynamics, owing to the decrease in the ratio of the gases enthalpy stream to the electrode processes energy loss. The final result is periodical cooling of the furnace bed during the release. This effect should be compensated by a suitable accumulative lining in the flue gases channel before the recuperator. Semi-closed furnace design moulds the process gases stream gas-dynamics significantly. Improper distribution of oxidizer streams leads to faster wear and tear of the device. Therefore, it is extremely important to select the best gases paths and distribution paths of after-combustion air and air cooling the electrodes and roof of the cap. Fan failure of the dedusting unit can damage the flue gases channel in the case of a sudden increase in temperature.

5. Conclusions

To successfully implement the combined process with well-known energy characteristics one must combine practical knowledge of durability, material and flow parameters, and expertise in process rudiments.

In heterogeneous responsive systems, an effective method of modeling is based on a non-stoichiometric attitude and free enthalpy minimization.

Due to differences in combustion velocity of the main components (CO, H_2, H_2S, CH_4, C_2H_4, SiO) the best results in the gaseous area above the charge can be obtained through kinetic models. Ongoing reaction processes significantly influence flue gases system characteristics and the heat recovery installation. Efficient use of recuperator system heating areas is possible with the use of 3D modeling.

Numerical analysis significantly contributed to the implementation of technical assumptions. An important stage in the analysis of the design was appropriate division of the device into research-balance subsystems, which allowed us to simplify the numerical procedure of the design.

In the scope of CFD modeling of high-temperature processes, the tools available allow for an increasingly higher degree of precision. In process optimization, CFD modeling is not an aim in itself, but becomes a tool for analysis. It seems vital to change the approach to this type of modeling, namely, we have to create a new kind of knowledge associated with the multidisciplinary integration of individual processes. Multidisciplinary integration makes it possible to design innovative constructions for devices, but one should first check the correctness of the modeling against actual measurement results.

Acknowledgments

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