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Thermal Physics as the Basis for Energy and Resource Conservation in Steelmaking

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Abstract—This article outlines improvements in metallurgical technology achieved on the basis of the integration of thermal physics and information science by the Ural school of specialists in metallurgy and thermal physics. In recent years, mathematical modeling, combined with physical modeling, has significantly reduced the optimization time in the thermal design and debugging of new technologies and equipment. Sintering machines have been modernized by introducing automatic control of the thermal and gas-dynamic processes and by designing new ignition hearths. These measures, besides improving heat and mass transfer, have boosted the performance of sintering plants in Russia and elsewhere, while reducing their environmental impact. In pellet roasting, a refined gas-flow system has been organized, and the gas lines have been reconstructed. As a result, the productivity has increased by 10–17%, with 8–15% decrease in the fuel consumption. The losses of gas after purification have fallen by 50–58%. Roasting machines in Russia, Brazil, and Iran have been reconstructed. In recent years, software has been developed for blast furnaces and introduced at Russia's largest steelworks: OAO Magnitogorskii Metallurgicheskii Kombinat. In blast furnaces, new air heaters for the blast produce temperatures of 1300°C or more by means of furnace gas and air, without added natural gas. In addition, systems processing metallurgical liquid slag at rates of 3–15 t/min and producing granulated slag at a rate of 0.66–2.0 million t/yr have been built at Russian, Ukrainian, Indian, and Chinese steel plants. A system is also operating successfully at the Norilsk Nickel plant. The thermal conditions in heating furnaces and equipment of various types have been improved on the basis of mathematical simulation of thermophysical processes by means of a dynamic zonal–point model of radiant and complex heat transfer. This method performs well in practice. In recent years, new furnace designs have been developed, and hundreds of heating furnaces have been modernized. Optimal thermal organization has significantly reduced fuel consumption, improved heating of the metal, and resulted in higher quality of the heat-treated product.

Keywords: mathematical modeling, sinter, pellets, blast furnaces, air heaters, liquid slag, heating systems, optimal organization

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The first theory of metallurgical furnaces was developed by Grum-Grzhimailo, whose hydraulic theory of furnaces may be regarded as the starting point of the discipline now known as thermal physics [1]. Decades of theoretical, experimental, and industrial research have brought thermal physics to its present level of development.

As applied to metallurgical technology, thermal physics combines four broad regions of scientific knowledge: thermodynamics; the theory of heat and mass transfer; molecular physics (the theory of metallurgical processes); and fluid mechanics and the mechanics of batch motion in furnaces.

In recent years, the integration of thermal physics and information science has yielded improvements in metallurgical technology. Mathematical modeling has significantly reduced the optimization time in the thermal design and debugging of new technologies and equipment. Physical modeling of metallurgical processes, on the one hand, provides the thermophysical characteristics required for the mathematical models—the thermal conductivity, specific heat, heat-transfer coefficients, etc.—and, on the other, permits adaptation of the model to the specific production conditions.

Of course, improvements in energy and resource conservation depend on scientists capable of formulating laboratory and industrial experiments and also of mathematical modeling and analysis of the results. The Ural school of specialists in metallurgy and thermal physics, one of the oldest in Russia, was organized by B.I. Kitaev. Its creative work has been largely undertaken at Ural State Technical University–Ural Polytechnic Institute (in the departments of metallurgical furnaces and of hot metal metallurgy) and also, since 1998, at Yeltsin Ural Federal University (in the departments devoted to thermal physics and information science in metallurgy and to the metallurgy of iron and steel). Institutions that have played an important role in the development of this school of thought include OAO NII Metallurgicheskoi Teplotekhniki (VNIIMT); the Institute of Metallurgy, Ural Branch, Russian Academy of Sciences; OAO Ural'skii Institut Metallov; OAO Uralmekhanobr; OOO NPVP TOREKS; and the Energotsvetmet Design Bureau. Thanks to their creativity, considerable progress has been made in developing a theory of thermophysical processes that has permitted energy and resource conservation in metallurgical systems, not only in Russia but around the world.

MATHEMATICAL MODELING OF THERMOPHYSICAL PROCESSES

Today, research attention is focused on the maximum possible utilization of equipment and the thermal and reducing potential of gases and ultimately on the maximum efficiency of thermal systems in metallurgy. In this context, it is very important to develop a theory of metallurgical systems—that is, mathematical description of the physicomechanical, thermal, and chemical processes in such systems and the creation of the corresponding mathematical models.

Despite progress in information science, the development of computational mathematics, identification algorithms, and banks of certified (verified) mathematical models has been slow, primarily because considerable resources of intelligence and time are required in the creation of satisfactory mathematical models of complex processes and systems. We note a dilemma here: as a rule, complex new processes and systems cannot function without a control system, while the mathematical model generally cannot be identified and certified without the existence of an actually functioning system.

The following are preconditions for the mathematical modeling of thermophysical processes in metallurgy.

(1) The broad use of the general theory of systems and system analysis. The need to solve problems in very different spheres of human activity calls for methods and approaches permitting the development of uniform technology for the investigation of systems of any kind. The general theory of systems integrates principles that are applicable to systems of different type. Metallurgical thermal physics is a component of the general theory of systems [2–4].

(2) The development and broad use of numerical methods for the solution of heat- and mass-transfer problems. Analytical solution of equations describing complex heat and mass transfer in metallurgical processes is practically impossible. As a rule, numerical methods permit their solution. The development and use of such numerical methods was reviewed in [4, 5].

(3) Improvement in the models by taking more complete account of the blast, gas-dynamic, and slag conditions, the mechanics of batch motion, and the available information regarding the operation of thermal systems in metallurgy [6–14].

(4) The availability of commercial software for thermophysical calculations. Despite clear limitations in formulating boundary conditions and describing real metallurgical systems, software such as ANSYS, COMSOL Multiphysics, MatLAB, Maple, Star-CD, Flow Vision, and SolidWorks provides significant assistance in studying and improving metallurgical technology. However, only Mathcad, Maple, and MatLab software is accessible to researchers. The other products are very expensive for university use. For scientific and practical purposes, individual products seem to have too many capabilities. However, this conclusion may simply indicate the need for more study.

(5) The use of modern technologies to develop of control software that is applicable to thermophysical processes in metallurgy [15–18]. For example, functional modeling is widely used to formalize mathematical models and design algorithms. Such modeling is based on concepts from the IDEF0 structural analysis and design procedure and the principles of structural system analysis and involves the formalization of a procedure-oriented approach in terms of data flow diagrams (DFD). These approaches permit effective transfer of information regarding the description and analysis of model systems between specialists in thermal physics and metallurgical technology and the developers of information systems. The program code in model systems is based on the Agile method, which is a flexible methodology for software development oriented to the use of iterative development, the dynamic formulation of functional requirements, and their incorporation in software in dialog with the system users.

IRON-ORE PREPARATION

Sinter Production

Among the institutes that actively collaborate with Yeltsin Ural Federal University, OAO VNIIMT is one of the few that has maintained its research capabilities in metallurgical thermal physics after the collapse of Russia's network of research organizations. On the basis of thermal physics and information science, OAO VNIIMT has facilitated the application of insights from theoretical thermal physics at metallurgical plants, at every stage of production from iron-ore preparation to the production of high-quality steel products.

In recent years, OAO VNIIMT has developed a sintering machine with recirculation of the sintering gas (under automatic control), a system for supplying hot gas to the batch bed [19], and an automatic safety system capable of maintaining CO concentrations below the limiting permissible level in the working area. The introduction of this design at four machines in sintering plant 2 of OAO Chelyabinskii Metallurgicheskii Kombinat significantly reduced the fuel consumption (by 3.6–3.8 kg/t of sinter), the content of fines in the final sinter (by 2.0–2.5%, abs.), and the dust and CO emissions to the atmosphere (by 26–28%).

Physical and mathematical modeling proved no less effective in creating a method for roasting sinter batch [20–22] and roasting hearths equipped with automatic thermal and gas-dynamic control systems. Sintering machines of different types, using different gaseous fuels, have been investigated. The characteristics of the new roasting hearths are as follows:

—minimum consumption of the fuel's heat of combustion in roasting the batch and improvement in sinter quality;

—increase in the working life of the sintering-tray components on account of fan-driven air cooling, without water coolers;

—decrease in furnace size and in heat losses to the surroundings on account of the design of the hearth's roof.

The results of this research were introduced in 13 sintering machines at OAO Chelyabinskii Metallurgicheskii Kombinat, OAO Vysokogorskii Gorno-Obogatital'nyi Kombinat, AO Ural'skaya Stal' (Russia), and OAO Zaporozhstal' (Ukraine), as well as at PAO Uralmashzavod, OAO MMK, Visakhapatnam and Bokaro steel plants (India), and Aksa Ferroalloy Plant (Kazakhstan). The operation of these hearths was accompanied by decrease in gaseous-fuel consumption of 7 kg/t of sinter.

On the basis of a mathematical model describing the sintering of iron ore from different fields, the operation of the roasting heath and the sinter-cooling units, and the gas-dynamic characteristics of the sintering batch and the sintering machines, OOO NPVP TOREKS proposed three thermal systems for sintering machines with hybrid cooling [23]. These systems take account of the need to separate the exhaust gases from the sintering machine into two or more fluxes characterized by different temperature, moisture content, and composition. One flux may be returned to the sintering process, while the second is used for energy purposes, and the third is sent to the system for the trapping and processing of individual elements such as S and Zn [23].

Adoption of these designs at OAO Severstal', OAO Mechel (Russia), and AOOT ISPAT Karmet (Kazakhstan) confirmed their effectiveness. A somewhat different and less effective approach is employed outside Russia [24].

The three-dimensional mathematical (dynamic) model of sintering offers considerable scope for the analysis of sintering and the development of energy- and resource-conserving systems [25–27]. This model takes account of all the basic thermophysical phenomena in sinter production. The developers of the model note that, "in terms of the precision and scope of its description, it outperforms all local balance methods and existing complex models" [27]. Thermophysical analysis of sintering on the basis of mathematical modeling has permitted the design and reconstruction of sintering plants in Russia and elsewhere (Ukraine, Kazakhstan, India, Yugoslavia, Egypt, Hungary, Iran, and Algeria). For example, the reconstruction of sintering machine 7 at sintering plant 2 of ArcelorMittal Temirtau steelworks increased its productivity by 30%.

Sinter production may be improved by applying an acoustic field to the batch bed. The influence of the acoustic field was assessed by specialists at Yeltsin Ural Federal University, in research on an enlarged Aglochasha laboratory system and in industrial conditions at the sintering plant of OAO Serovskii Metallurgicheskii Zavod [28]. Acoustic radiators in the form of Hartman tubular waveguides were installed in the first two vacuum chambers. The compressed-air pressure was 3.0 atm. and the total compressed-air consumption per radiator was no more than 50 m^3/h. In investigating the influence of the acoustic field on the batch bed, the batch composition and all the operations corresponded to the traditional technology.

The acoustic field induces vibration of the grating and reaches the lower levels of the sintering batch (the raw and dried layers). It extends to the combustion and melting zones. Bed particles and dust are entrained in the vibrational process. That decreases the boundary-layer thickness in the pore channels at the surface of the solid bed components and intensifies mass transfer. The bed of fine particles is loosened, which permits increase in the flow rate of the heating gas. That stimulates the heat and mass transfer in the batch bed, with simultaneous decrease in dust entrainment on account of its deposition in the batch bed and also in the vacuum chambers.

In industrial tests of acoustic radiators (total acoustic power 1.0–1.2 kW/m^2) in the vacuum chambers, with an acoustic field covering no more than 15–20% of the sintering area, and of radiators (acoustic power of 0.3–0.4 W/m^3) also in the collection volume, researchers noted increase in productivity by 3.2–8.3%, decrease in the dust content of the sintering gases by 29.2–36.2%, and decrease in CO concentration in those gases by 26.7–33.4%.

Similar improvement in energy efficiency and atmospheric emissions are possible in pellet roasting.

The sintering of iron ore may be improved if the thermal conditions are the same over the height of the bed of sintering batch. To create thermal conditions in which those conditions are satisfied, a system for the combustion of solid and gaseous fuel (hybrid fuel) in the sintering bed was developed in the department devoted to thermal physics and information science in metallurgy, with tests in industrial conditions [29].

A special distributor for the supply of natural gas and air above the sintering bed may be installed in the roasting hearth, after a stable zone of solid-fuel combustion has already been established in the bed. The gas–air mixture formed in the space between the distributor and the bed surface passes through the hot sinter layer in the upper part of the batch bed and heats it to the ignition temperature (450–600°C), with the formation of an active combustion zone (40–60 mm) at 1100–1150°C. The heat liberated here further raises the temperature of the upper bed levels to the required sintering temperatures.

Industrial tests of the gas–air distributor on the sintering machine at OAO Serovskii Metallurgicheskii Zavod indicate that the use of hybrid fuel equalizes the heating conditions over both the height and width of the batch bed. With increase in natural-gas content in the gas–air distributor to 40%, the productivity of the sintering machine is increased by 30–35% and the yield of small fractions in the drum sample is reduced.

Pellet Production

In recent years, researchers have sought means of improving the quality of iron-ore pellets for use in blast furnaces and alternative iron-production technologies [30–32].

To eliminate the nonuniform heat treatment of the pellets over the bed height in roasting machines of conveyer type and to improve pellet quality, researchers in the department devoted to thermal physics and information science in metallurgy have developed devices for gas combustion in the bed and thermal systems for conveyer roasting machines and tested them in industrial conditions. Since the roasting of gas in the bed provides an additional source of thermal energy, this is sometimes known as hybrid roasting technology [33].

Such technology is organized as follows: drying and heating of the pellet bed, as already described; and roasting of the pellets in the upper layers (to a depth of 75–100 mm) at 1200–1300°C, by means of the products of gas combustion in the hearth. Then a cold gas–air mixture (air excess $\alpha = 3.0–5.0$) is sent to the bed and, as it passes through the hot material, heats it to the ignition temperatures. Stable gas combustion begins in the bed. The combustion products of the gas–air mixture pass through the lower layers and heat the pellets there. As the pellets are heated to the temperature corresponding to ignition of the gas–air mixture, combustion travels lower in the bed. That ensures uniform heating of the pellets to the specified temperature over the whole bed height.

The introduction of this approach in two conveyer roasting machines at Kachkanar enrichment facility demonstrated the reliability of the gas burner employed, which ensures safe and stable gas combustion in the pellet bed. The new technology not only eliminates the nonuniformity of pellet heat treatment over the bed height in conveyer roasting machines and improves pellet quality but also increases the productivity by 10–12% in comparison with the traditional technology, reduces natural-gas consumption by 10–15%, and reduces energy consumption by 6–8% [33].

Specialists at OOO NPVP TOREKS have developed a new thermal system for the MOK-1-592 roasting machine at Mikhailovskii enrichment facility [34, 35]. This approach involves the organization of a three-section drying zone, refinement of the gas-flow configuration, and reconstruction of the gas lines [36, 37]. Reconstruction of the MOK-1-592 roasting machine on those principles increased its productivity by 10–17%, reduced the fuel consumption by 8–15%, and reduced the total release of purified gases to the atmosphere by 50–58%. The same principles were adopted in reconstructing roasting machines 1 and 2 at Mikhailovskii enrichment facility [37, 38]. Experience with the fourth-generation roasting machine provided the basis for the reconstruction of all the roasting machines at Russian steel plants. In addition, reconstruction projects are underway in Brazil and Iran under the guidance of specialists from OOO NPVP TOREKS.

Profound research on pellet roasting is underway at OAO VNIIMT, whose specialists have introduced a newly designed conveyer roasting machine at AO Sokolovsko-Sarbaiskoe Gorno-Obogatitel'noe Proizvodstvennoe Ob''edinenie. As a result, productivity has increased by 24.6%, natural-gas consumption has been cut by more than half, and power consumption in the blast drives has been reduced by 21.3%. In addition, the plant's environmental impact has been reduced, thanks to the introduction of gas-purification systems and reduction in fuel and power consumption. Accordingly this machine matches the performance of its best global counterparts [39, 40].

BLAST FURNACES

There is a close relation between the blast-furnace shop at OAO MMK and the department devoted to thermal physics and information science in metallurgy at Yeltsin Ural Federal University [41–51]. In recent years, software such as the following has been developed for various aspects of blast-furnace operation and introduced at OAO MMK:

—integrated software for an automated engineering work station at the blast furnace;

—integrated software for the engineering staff in the blast-furnace shop;

—software for simulating blast-furnace processes and assessing the operational characteristics of the blast-furnace shop;

—image-recognition software for thermal prediction of metallurgical processes (in particular, in the blast-furnace shop);

—software for optimal distribution of natural gas and oxygen among the blast furnaces;

—software for selecting the deliveries of raw materials and the optimal batch composition in sinter production;

—software for control of metallurgical systems (and in particular, in the blast-furnace shop) at startup;

—software for thermal and gas-dynamic simulation of blast-furnace operation when using pulverized coal.

The use of simulation and information systems improves the staff's decision making in the case of unstable composition and quality of the iron and the fuels and changes in market conditions. The software for blast-furnace operation with pulverized coal permits thermal and gas-dynamic simulation of blast-furnace operation and the solution of various technological problems.

In the department of iron and steel metallurgy at the Institute of New Materials and Technology, Yeltsin Ural Federal University, researchers have developed a mathematical model of the thermal state at the bottom of the blast furnace, on the basis of the laws of heat and mass transfer (taking account of the thermodynamics and kinetics of impurity oxides). This model permits calculation of the temperature distribution of the gas, coke, slag, and hot metal over the furnace height. In addition, the model permits analysis of the reduction of impurities from oxides in the hot metal. On that basis, the smelting of hot metal from vanadium-bearing titanomagnetites may be organized, with less than 0.1% Si in the hot metal. Measures to suppress titanium-carbide formation and optimize the slag conditions may also be identified [52–55]. These measures reduce the coke consumption by more than 10 kg/t of hot metal and result in a productivity of more than 3.0 t/m^3.

At the Institute of Metallurgy, Ural Branch, Russian Academy of Sciences, a method has been developed for assessing the influence of the iron ore (specifically, its ease of reduction, strength, softening temperature, and melting point) on the blast-furnace process [56]. This method is based on mathematical models of blast-furnace operation [57, 58]. It may be used to improve the processing of iron ore and to expand the available sources of iron.

The Institute of Metallurgy has proposed a system for separate extraction of low-titanium and high-titanium ore from the Guserovsk field, in collaboration with the Mining Institute, Ural Branch, Russian Academy of Sciences [59]. Likewise, in collaboration with AO EVRAZ KGOK and OAO EVRAZ NTMK, specialists at the Institute of Metallurgy have developed means of improving sinter quality and reducing coke consumption in the blast furnace [60]. In collaboration with OAO Uralmekhanobr, the Institute of Metallurgy has proposed a processing technology for titanomagnetite ore from the Tebinbulak field (Uzbekistan) on the basis of a blast furnace and a converter [61]. The system developed at the Institute of Metallurgy for monitoring the refractory lining in the hearth is operating successfully at five Chinese blast furnaces [62]. There are plans to introduce it in one of the blast furnaces at OAO MMK.

BLAST HEATERS

Many factors ensure the stable thermal operation of blast furnaces, which is required in order to ensure high productivity and low coke consumption. The use of hot blast is of considerable importance here. In recent years, Kalugin shaftless air heaters have been widely adopted to heat the blast. Today, 194 such heaters operate at steel plants around the world, ensuring blast temperatures of 1000–1150°C or even 1200–1250°C at some Russian and Chinese plants [63].

Research indicates that it is expedient to heat the blast to 1300°C or more, with considerable economic benefits. Thermophysical analysis at ZAO Kalugin shows a real possibility of attaining such temperatures if a temperature of 1430°C is maintained under the cupola of the Kalugin air heater by heating the blast-furnace gas and the air used in blast heating, without adding natural gas. This may be accomplished by means of thermal siphons, mounted at the flue ahead of the smokestack. The installation and operation of the thermal siphons proves less expensive than the acquisition, processing, and delivery of the fuel otherwise added to the blast-furnace gas [64].

To confirm the energy efficiency of this approach, the process of heating the packing and the blast in a 2700-m^3 blast furnace producing regular hot metal is analyzed. The blast-furnace productivity is ensured by the supply of blast at a rate of 5400 m^3/min. For the baseline period, the blast temperature is 1250°C, the blast-furnace gas and oxygen supplied to the Kalugin air heater are not heated, and the blast-furnace gas is enriched with natural gas supplied at a rate of more than 5600 m^3/h. In the trial, the blast-furnace gas and oxygen supplied to the Kalugin air heater are heated to 200°C by means of combustion products at 300°C, and no natural gas is added to the blast-furnace gas. In these conditions, the temperature in the cupola of the Kalugin air heater is 1430°C and the blast temperature is 1310°C. Note that, in the trial period, the fuel consumption in the heating of 1000 m^3 of blast is reduced by more than 2.0%. In terms of conventional fuel, the annual saving is 4210.7 t.

ZAO Kalugin has amassed considerable experience in the design, manufacture, installation and debugging of heat exchangers based on thermal siphons. Thanks to that experience, 48 Russian and Chinese blast furnaces currently operate with thermal siphons [65].

PROCESSING LIQUID SLAG

Globally, OAO VNIIMT is one of the first enterprises to analyze slag processing in terms of thermal physics.

Researchers at OAO VNIIMT have developed successful approaches for the processing of liquid slags from ferrous and nonferrous metallurgy on the basis of thermal physics and its primary subdisciplines: heat exchange and hydrodynamics. Attention turned first to the spraying of slag and the organization of the motion of cooled slag pulp. In studying the heat transfer in the separation and cooling of liquid jets by water, the water flow rates and limiting size of the slag particles were established. Even the considerable quantities of hot metal entrained by slag from the furnace do not create explosive conditions: under the action of the water jet, the hot metal breaks down into small droplets, each of which has a heat reserve too small to incite explosive vaporization. On the basis of the hydrodynamics of slag-pulp motion, an airlift system was developed. This research led to the installation of a granulation unit for liquid slag in the blast-furnace system [66]. Granulation offers the following benefits:

—improvement in the working conditions;

—relatively simple control and the potential for completely automatic operation;

—processing of all the blast-furnace slag to obtain a high-quality product for cement production;

—localization of toxic vapor–gas emissions and their systematic removal;

—neutralization of sulfur compounds present in the vapor–gas emissions;

—production of high-quality granules without risk of explosions;

—breakup and cooling of the slag melt by means of recycled (slightly clarified) water;

—evacuation of the thickened slag–water pulp by a reliable and abrasion-resistant airlift method;

—drying of the slag–water pulp in a continuous carousel system;

—drying of the granulated slag by means of its own physical heat.

Analysis of the operation of such units at plants in Russia, Ukraine, India, and China confirms their high productivity: slag throughput 3–15 t/min; annual slag processing 0.66–2.0 million t [67]. Prolonged operation of the units has confirmed that they are explosion-safe. Experience in the granulation of liquid slags in steelmaking has been employed in the production of a similar unit for use in nonferrous metallurgy, at Norilsk Nickel [68].

Today, OAO VNIIMT is the main developer of granulation units for liquid slag that may be used with blast furnaces of capacity 2000–6000 m^3 [67].

It is of great interest to utilize the high-potential heat found in liquid slag. Researchers at OAO VNIIMT have developed a system for dry granulation of slag melt based on the solidification of the slag by means of solid coolant. This technology is ready for industrial introduction.

GAS SYSTEMS AT BLAST FURNACES

At Yeltsin Ural Federal University and OAO VNIIMT, research work is underway on the mathematical modeling of thermophysical processes in the working space of furnaces and other systems. For example, a dynamic zonal–point method of modeling radiant and complex high-temperature heat transfer is under development [69]. Mathematical modeling of the heating of pipe and pipe blanks in sectional furnaces at Seversk and Pervouralsk pipe plants has provided the basis for the reconstruction of those furnaces. The reconstruction reduces the fuel consumption by 15–20%, increases furnace productivity by 20–30%, and reduces the emission of nitrogen oxides. This method has been tested at the Gas Technology Institute (United States) [70]. Currently, it is known worldwide as the DFI heating method (direct flame impingement).

Other projects include the following.

(1) In the heating furnaces at Pervouralsk pipe plant, specialists are introducing improved heat treatment of the pipe, direct measurement of the metal temperature, and gas-dynamic control of the furnace working space. In annular furnaces at Seversk pipe plant, ribbed floors are being installed to increase the working life [70].

(2) A model method has been introduced for the blast furnace's expert system [71].

(3) Energy and environmental analysis has been further developed, including the determination of the technological fuel numbers and the toxic and greenhouse emissions. Numerous metallurgical processes are now under analysis by that means [72].

(4) Metallurgical technologies with and without coke are being appraised and recommendations are being formulated for the development of technologies with minimum environmental emissions. In particular, the direct alloying of steel by vanadium is being refined. Elements of this process are already in use in Russia and elsewhere, with decrease in the vanadium losses by a factor of 3–4 [73, 74].

Historically, in studying the heating and cooling of metal, researchers in the department devoted to thermal physics and information science in metallurgy have generally focused on improving the structure and thermal conditions of the furnaces. Collaboration in this research with design and research organizations ensures the design and construction of thermal systems according to the latest technology. Serious attention is also paid to the energy efficiency of thermal systems, with the introduction of up-to-date high-speed gas burners utilizing the heat from the combustion products leaving the furnace. That permits 50% decrease in the consumption of natural gas by comparison with traditional methods [75].

The collaboration between researchers in the department and the UralTermoKompleks manufacturing company may be illustrated by the following projects.

(1) At the Kirov plant for nonferrous-metal processing, two push-rod furnaces and one stepping-hearth continuous furnace for heating copper-alloy slabs (2–5 t) have been developed and put into operation. Fibrous blocks are used for the furnace lining. The furnace is equipped with up-to-date high-speed gas burners and an automatic thermal control system [76].

(2) At the Kashira metal-structures plant (in the Moscow region), a distinctive chamber furnace with fibrous lining and high-speed recuperative burners has been designed and constructed. This furnace is characterized by variable geometry of the working space, depending on the size of the object to be heated. A rolling-floor system permits adjustments of up to 60 m [77].

(3) At Uralmashzavod (Yekaterinburg), a vertical thermal process for long machine components of variable cross section (rotor turbines, rollers for steel-sheet production) has been developed and put into operation. This furnace is lined with ceramic-fiber blocks. High-speed recuperative burners are installed. An automatic thermal monitoring and control system governs the heat treatment of metal parts. An improved technology is used to cool the parts after their heating in the furnace to the required temperatures. The metal is cooled by air supplied to the furnace through the recuperative burners, by means of a fan. This is associated with continuous decrease in temperature of the metal and correspondingly of the air. Such soft cooling rules out the formation of thermal stress in the parts and hence prevents cracking [78, 79].

Automatic thermal control systems may be widely introduced at metal-heating furnaces on the basis of mathematical models of each heating process (and, where necessary, cooling process). That permits the organization of metal heating without human intervention. The new thermal conditions are associated with considerable (up to 50%) decrease in natural-gas consumption and decrease in greenhouse-gas emissions, the most dangerous of which are CO, NO, N_2O, NO_2, and SO_2.

The researchers at OAO VNIIMT and Yeltsin Ural Federal University have also had success in modernizing various types of metallurgical furnaces. Accomplishments include the selection of a regenerative or recuperative heating system with the appropriate gas burners; determination of the optimal number of heat control zones; the use of ceramic-fiber furnace linings; optimization of the working space's dimensions (in particular, the roof height); monitoring of the combustion-product composition in different zones and in the flue; automation of the control systems on the basis of programmable controllers; and development of the best thermal conditions in furnaces on the basis of modeling and analysis [80].

In the heat treatment of metals, electric furnaces are often used. Electric power offers certain benefits, but particular attention must be paid to the energy consumption. The cost of electrical heating is 1.5–2 times that of gas heating, while the capital costs are 7–8 times higher. OAO VNIIMT has experience in converting from electrical to gas heating.

Research at OAO VNIIMT on the combustion of gaseous fuel has been used in the development and certification of gas burners based on different gases and used for different purposes. The recuperative gas burner developed at OAO VNIIMT outperforms its non-Russian counterparts in terms of air temperature and air flow rate with the smokestack gases [81]. Recuperative burners are used when the temperature of the heating gases in the furnace is no more than 1000–1050°C. Researchers at OAO VNIIMT have also developed compact regenerative burners used in various furnaces. The first Russian chamber furnace based on such burners was built at the VSMPO plant (Verkhnyaya Salda) in 2000 [82]. Burner control is completely automated. This design reduces the natural-gas consumption by 55%. More than ten reconstruction projects have been undertaken for furnaces of various types.

It is difficult to underestimate the role of thermal physics in the creation of systems for the heat treatment of metal and alloy parts. This is particularly evident in that parts of different thermal mass and shape must be heat-treated so as to ensure excellent mechanical properties. Traditional quenching in water, oil, saltpeter, and alkali baths cannot ensure the required strength, structure, etc. The controlled high-speed water–air cooling developed by OAO VNIIMT is based on the laws of temperature variation at the surface of the part (convective heat transfer) and within the part (conductive heat transfer). Thus, the thermal stress in the part is monitored. The cooling rates of different elements of the part are controlled over a broad temperature range by changing the density of the water–air flux, which may vary over the heat-treatment cycle, without permitting the development of undesirable mechanical properties, structure, etc. Researchers at OAO VNIIMT played an active role in the development of water–air cooling in collaboration with plant staff and thermal-physics specialists at Yeltsin Ural Federal University [83].

Water–air cooling has been successfully introduced, for example, in the heat treatment of railroad wheels, rails, rail beds, alloy sheet, pipe, ShKh-15 bearing races, and manufacturing components. The strengthening of sheet steel on the Severstal' 5000 mill has no counterpart anywhere in the world. The heat treatment of rail beds by this technology increases the strength by a factor of three and the hardness by a factor of 1.2–2.5; the operational life is increased by a factor of 2–5 [84]. These accomplishments may be attributed to the complete utilization of the potential of water–air cooling [83–86]. The costs of heat treatment are considerably reduced, because there is no need for oil, saltpeter, or washing fluids. This technology offers considerable scope for further development.

Researchers at OAO VNIIMT and at Yeltsin Ural Federal University are actively collaborating in exploring the thermal physics of metallurgical technologies and elsewhere, with the development of improved or new technologies, such as the following.

(1) Considerable success in drying technologies for crushed materials. For example, the drying of friable materials by means of solid heat sources reduces the time required by a factor of 10–20, while the size of the necessary equipment may be reduced by an order of magnitude [87].

(2) A new technology for processing of iron ore and concentrate by means of an electric arc. This system is more compact than the traditional equipment; there is no need for pelletization or pellet roasting; and the metal and slag are separated [88].

(3) New drying technology and equipment for the lining of hot-metal, steel-casting, and other ladles, developed on the basis of thermophysical analysis of the heating and cooling of the lining. This technology permits two- or threefold increase in working life of the ladles, with decrease in fuel consumption by a factor of 5–10 [89].

(4) Improved pellet processing by Midrex technology at Oskolsk Electrometallurgical Works. Modernization increases the productivity by 15–50% and reduces the natural-gas consumption by 5–7% [90].

(5) Technology and equipment for processing oily scale at Sinarsk pipe plant. The product is less expensive than ore concentrate by a factor of 2–2.5, and the plant's environmental impact is decreased [91].

CONCLUSIONS

Researchers are actively developing thermal physics in both ferrous and nonferrous metallurgy.

(1) Mathematical modeling of heat- and mass-transfer processes typical of metallurgy, taking account of the motion of gas and materials.

(2) Physical modeling of metallurgical processes to determine the parameters required in order to generate mathematical models and adapt them to industrial technology.

(3) Extensive study of the development of metallurgical processes.

(4) Analysis of metallurgical technology in terms of energy efficiency, resource conservation, and environmental impact.

(5) Improvements in metallurgical technology and equipment with a view to better performance and reduced environmental impact.

(6) Formulation of principles for the development of control systems applicable to metallurgical processes.

In the last few years, research based on the precepts of thermal physics has considerably improved metallurgical technologies in terms of product quantity, productivity, fuel consumption, greenhouse-gas emissions, and the utilization of secondary resources. This is evident from the accomplishments of the Ural school of specialists in metallurgy and thermal physics that are noted in this article and elsewhere in the current issue of this journal.

Note, in conclusion, that the findings of thermal physics in relation to metallurgy have continually been passed along to students, who are the future of the industry.

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