Open Joint Stock Company
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OJSC Scientific-Research Institute of Metallurgical Heat Engineering (VNIIMT) established in 1930 as Ural Division of All-Union Heat Engineering Institute is widely known in Russia and the CIS. The Institute focuses on development of high-technology heat engineering units, energy efficient and ecologically friendly technologies in ferrous and non-ferrous metallurgy, machine-building and other fuel-consuming branches of industry.

Highly-qualified academic researchers, unique experimental and production facilities and own research and design centre enable efficient scientific-and-research, design-and-experimental, engineering and project works, delivery of equipment, designer's supervision and commissioning works including execution of turnkey contracts in the following areas:

**Sintering:**

- development of techniques and modes of metal raw material heat treatment;
- design of energy-efficient agglomeration hearths and agglomeration gas heat recovery circuits allowing to reduce energy consumption and dust and gas emissions.

**Pellet production:**

- optimal traveling grate pelletizing furnaces for heat treatment of iron-ore pellets from various concentrates (hematite, magnetite, etc.) with optimal automatic process control system.

**Preparation of metallic and nonmetallic raw materials:**

- technique of iron-ore raw material dephosphorization by roasting and leaching;
- installations for drying high-moisture dispersive materials of various designs;
- efficient techniques of magnetizing roasting and subsequent dressing;
- technique of rare-earth element extraction (for example, germanium from germanium iron ores).

**Blast-furnace ironmaking:**

- explosion-proof near-furnace systems of blast furnace slag granulation giving a high-quality product for cement production;
- optimal control system for hot blast stoves;
- an innovative bench for drying hot metal and steel-smelting ladles;
- copper coolers and tuyeres of blast furnaces.

**DRI (direct reduction of iron)**

- improvement of the reduction technique in shaft furnaces for radical improvement of technical and economic indicators of their operation (productivity is increased twice);
- technique of raw material reduction in rotary furnaces using coal as the reductant.

**Lime production:** development of the technique and increase of lime production process efficiency:

- in shaft furnaces;
- in double-shaft furnaces;
- in rotary furnaces;
- in “stacked-tower preheater - rotary furnace” installations;
- in “shaft calciner - rotary furnace” installations (VNIIMT innovative technology).

**Granulation of metal melts:**

- development of technologies and designs of explosion-proof plants for near-furnace granulation of metallurgical slag, molten metal, etc., including heat recovery;

**Reheating furnaces:**

- development of new and update of the existing designs of furnaces for stock heating;
- high-performance systems of reheating furnace firing with recovery and regeneration firing systems based on the innovative burner units designed by VNIIMT;
- switching the furnace firing systems to cheaper fuel types;
- development and implementation of optimal furnace operating parameters.

**Heat-treatment furnaces** development of techniques and equipment for heat treatment of roll stock and metal products including those with protective atmospheres:

- thermochemical treatment conditions ensuring retention or directional change in chemical composition of metal surface;
- gas dampers for heat-treatment furnaces;
- spray quenching units and other elements of convective cooling systems;

**Furnaces with protective atmosphere and gas treatment units:**

- development of the furnace structure, design, manufacture, delivery and commissioning works;
- development of a technology for treatment of articles and devices for protective gas generation;
- calculation, development and manufacture of endogas and exogas atmosphere generators for metal product thermochemical treatment units;
- gas analysis systems for monitoring and control of physico-chemical properties of protective process atmospheres.

**Reheating, heat-treatment and drying furnaces with convection heat transfer:**

- development, design and manufacture using industrial heat-resistant (up to 900 $^{o}$C) furnace fans designed by VNIIMT.

**Rolled products:**

- techniques and units for controlled high-speed air-to-water cooling (quenching) of rolled ferrous and non-ferrous metal products including thick plate on mill 5000;
- replacement of oil quenching technology with VNIIMT's eco-friendly air-to-water technique;
- innovative technique of oily mill scale processing;
- line of wire rod accelerated air cooling with process improvement.

**Manufacturing** manufacture and delivery of:

- high-performance burner units;
- heat-resistant (furnace) fans (up to 900 $^{o}$C);
- copper coolers for blast furnaces and nonferrous furnaces based on VNIIMT technology;
- Pitot tubes for measuring flow rates and pressures.

OJSC VNIIMT developments are widely used in metallurgical enterprises of Russia, Ukraine, Kazakhstan, China, India and others.

For detailed information on institute developments, please visit OJSC VNIIMT site at www.vniimt.ru

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ISSN 0967-0912, Steel in Translation, 2015, Vol. 45, No. 3, pp. 199–206. © Allerton Press, Inc., 2015.
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# Boosting the Hot-Blast Temperature in Blast Furnaces by Means of an Optimal Control System

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2 3 **Abstract**—Thermal analysis of the air heater for 2038-m$^3$ blast furnace 1 at OAO Chelyabinskii Metallurgicheskii Kombinat confirms that the hot-blast temperature may be increased by at least 30–40°C on introducing an optimal control subsystem designed by OAO VNIIMT. This reduces expenditures on coke by 75 million rub/yr.

*Keywords*: blast heater, optimal control subsystem, mathematical model, algorithm, optimization, thermal analysis

**DOI:** 10.3103/S0967091215030043

Boosting the blast temperature reduces the consumption of expensive coke and generally improves blast-furnace performance. Thermal analysis permits assessment of the blast-heater efficiency and determination of the scope for raising the blast temperature. We know that, besides improving the design of the blast heater and the packing, which is capital-intensive, the blast temperature and heater-efficiency may be increased by introducing optimal control systems for blast production on the basis of specific mathematical models.

At OAO VNIIMT, an optimal control subsystem for the blast heater has been developed, permitting 30–40°C increase in blast temperature. The primary characteristics of this subsystem are as follows:

—the use of a generalized predictive model of hot-blast production in heaters of different design;

—automatic identification of the model parameters.

In formulating the optimization problem, attention focuses on the blast temperature and the energy consumption.

## GENERALIZED PREDICTIVE MODEL

The model is based on the physical laws governing heater operation and employs the relevant heat-transfer and aerodynamic equations. The predictive aspects of the model offer the following capabilities:

—fast, precise, and reliable determination of parameters inaccessible to direct measurement;

—prediction of characteristics such as the blast temperature and gas consumption with variation in the control parameters.

The generalized predictive model includes components dedicated to specific elements of the heater (such as bricks of specific type employed over the heater height [1]). In particular, the heat transfer in the heater is described by partial differential equations; aerodynamic equations are employed; and the gas flow rate is predicted on the basis of the thermal and material balance for specific fuels (blast-furnace gas, coke-oven gas, neutral gas, or mixed gas), with allowance for the limiting burner parameters.

## ALGORITHMS FOR IDENTIFYING THE MODEL PARAMETERS

The model parameters that are most difficult to determine and most variable are the heat-transfer coefficient, heat-transfer surface, gas-dynamic drag, and thermophysical characteristics of the heater's 1
packing. If appropriate identification algorithms are constructed, the control parameters of the model may be corrected in response to technological changes, so as to improve the predictive accuracy and the model's description of the actual process, thereby facilitating optimal control.

## OPTIMIZATION ALGORITHMS

The optimization algorithms permit optimal control with limits on the maximum and minimum temperatures of the cupola, the boundaries between packing zones, and the devices within the heater chamber; the heating and cooling rates; the gas and air flow rates at the burners; and the duration of the gas and blast periods. The basic requirements in blast-furnace operation are as follows:

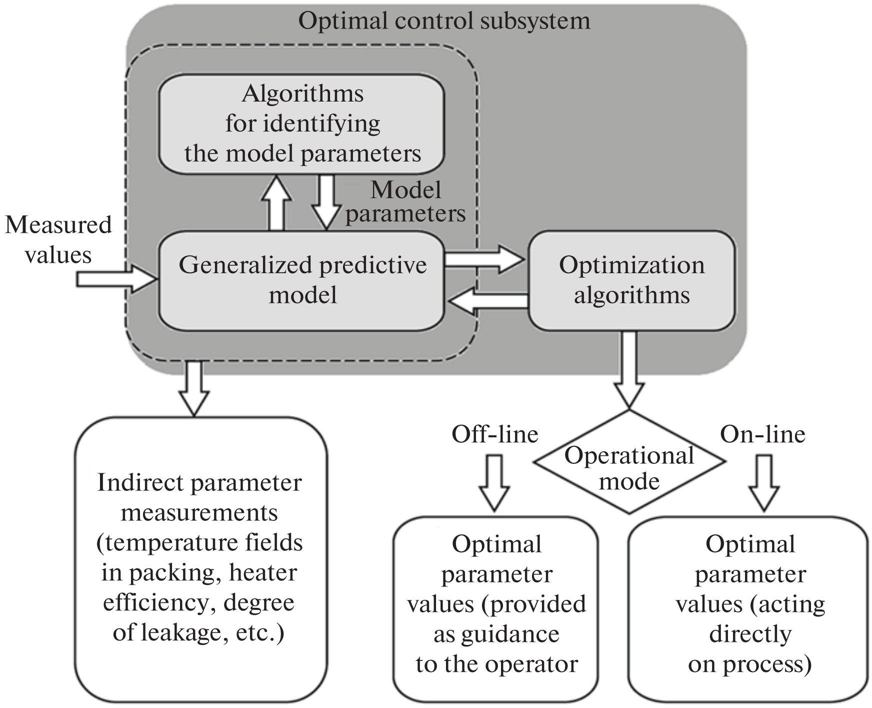


**Fig. 1.** Structure of the optimal control subsystem.

—maximum blast temperature;

—minimum cost in ensuring the specified blast parameters;

—maximum savings in terms of reduced heating costs and elevated blast temperatures.

Thus, the optimization algorithms ensure the required blast parameters, low energy consumption, and long life of the equipment. The algorithms are based on the generalized predictive model and permit determination of the values of the control parameters corresponding to maximum blast temperature or economic benefit with the constraints on the control parameters, taking account of the furnace conditions.

## STRUCTURE OF THE OPTIMAL CONTROL SUBSYSTEM

The structure of the optimal control subsystem is shown in Fig. 1. The measured process parameters are sent to the generalized predictive model. The model parameters are constantly corrected by the identification algorithm so as to minimize the discrepancy between the measured and calculated values and hence to improve the predictive accuracy and the model's description of the actual process.

On the basis of the model, the values of parameters inaccessible to direct measurement (such as the temperature fields in the packing, the heater efficiency, and the level of leakage) are determined and sent to the operator. Such indirect measurement allows the operator to more effectively control the process.

Using the optimization algorithm and the model, the optimal operating conditions of the blast heater are calculated, in accordance with the specified optimization criterion (for example, maximum blast temperature). Supplied to the control loops, these results automatically modify the process so as to optimize heater operation (on-line operation) or provide guidance to the operator (off-line operation).

We now consider the basic the scope for raising the blast temperature by means of the optimal control subsystem. We know that hot-blast production is accompanied by large fluctuations in calorific value of the blast-furnace gas (up to 40%), wear and damage to the heater (including combustion-chamber leakage and also melting and contamination of the packing), seasonal fluctuations in air temperature, and mutual influence of the heating elements. This results incomplete combustion of the gas and unnecessarily high gas consumption, reduced cupola temperature in the gas period, large fluctuations in the maximum temperature within the heater at the end of the gas period, and so on. As a result, the blast temperature is reduced, and excessive quantities of expensive coke are consumed in the blast furnace. Despite extensive research in this area, including research at OAO VNIIMT, we lack a clear understanding of how the main perturbing factors affect the blast temperature and the efficiency of the process.

In the present work, thermal analysis of the blast heater permits the identification of scope for raising the blast temperature on the basis of an optimal control

subsystem, for the example of blast furnace 1 at OAO
2 3 Chelyabinskii Metallurgicheskii Kombinat (ChMK).

## HEATER CHARACTERISTICS

The internal combustion chambers in the blast heaters at 2038-$m^3$ blast furnace 1 are lined with Dinas and mullite–corundum (MKV-72) refractories. The system contains (by design) four individual blast heaters operating in parallel pairs, so that two heaters act simultaneously on the blast; the blast switches from one set to the other after half the total blast period. The standard duration of the gas and air periods is 2 h; the total duration is 4 h; the valves reverse after 7–10 min.

The heater system employs purified blast-furnace gas, with the following mean composition: 20–24 wt % CO, 17–20 wt % $CO_2$, 7–9 wt % $H_2$, 0.4 wt % $CH_4$. No natural gas is added, and the calorific value is not corrected. The pressure of the blast-furnace gas entering the heater is stabilized at 550 daPa. The oxidant (air) is supplied individually to each heater by a D-60/310 fan (rated productivity 1000 $m^3$/min).

In thermal analysis, we employ the following data:

—the initial data for the structural parameters of the blast-heater system at blast furnace 1;

—the operational parameters (readings of the monitoring instruments for June 17–27, 2010);

—prior research data from OAO VNIIMT;

—measurements made by OAO VNIIMT and OAO ChMK specialists using portable instruments in July 2010;

—blast-heater software developed on the basis of OAO VNIIMT models.

## FLUCTUATIONS IN THE CALORIFIC VALUE OF BLAST-FURNACE GAS

In heater operation during the gas period (heating period), the blast temperature is reduced by fluctuations in the chemical composition and hence the calorific value of the blast-furnace gas. For example, according to measurements of the chemical composition and calorific value of the blast-furnace gas at OAO ChMK furnace 1 made with portable instruments in collaboration with researchers from the forerunner of OAO VNIIMT in 1981, the calorific value $Q_p^{co}$ of the blast-furnace gas varied from 2791 to 4300 kJ/$nm^3$ (by 13.4%). A numerical experiment based on these data shows that maintaining constant air excess $\alpha = 1.05$ (which is optimal for the combustion of blast-furnace gas) calls for a gas/air ratio in the range 0.77–0.89. In other words, maintenance of the maximum cupola temperature calls for ongoing correction of the gas/air ratio within a range of 14.5%. With no correction of the gas composition, the cupola temperature may be short of the maximum value by 65°C.

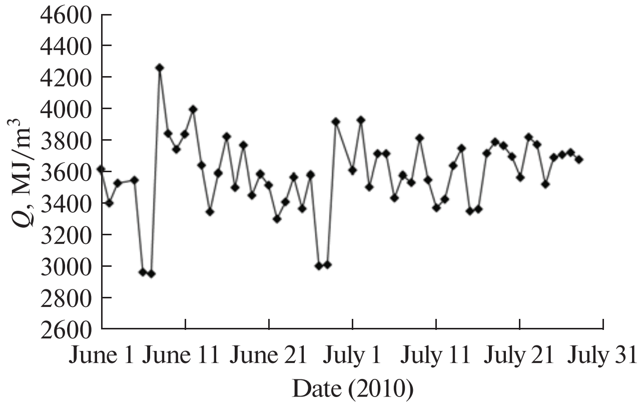


**Fig. 2.** Fluctuations in calorific value of blast-furnace gas.

In our research (June–July 2010), the variation in calorific value is even greater: 2954–4261 (44%), with a mean value of 3586 kJ/$nm^3$ (Fig. 2). In that case, maintenance of the maximum cupola temperature calls for correction of the gas/air ratio over an even greater range: from 0.6 (with minimum calorific value) to 0.87 (with maximum calorific value). In other words, we require variation over a range of 45%, which corresponds to change in the combustion-product temperature (with the optimal air excess $\alpha = 1.05$) from 1212 to 1459°C. With the mean calorific value (chemical composition), the temperature required is 1341°C. This is in good agreement with the mean maximum cupola temperature of 1338°C measured by the instruments for the blast-heater system between June 17 and June 27, 2010.

At present, the air consumption in combustion at the blast-heater system is not measured, while the gas/air ratio is regulated manually so as to maximize the cupola temperature. However, this method is characterized by considerable inertia and delay (on account of the inertia of the thermocouple in the cupola). No account is taken of the thermal state of the heater, which also affects the thermocouple readings, and sometimes the necessary quality of regulation is not maintained. It is especially difficult to obtain the maximum cupola temperature when the flow rate of combustion products through the heater must be adjusted, since that calls for manual (remote) control so as to proportionally change the flow rates of the blast-furnace gas and the air needed for combustion. Those flow rates are estimated from the experimental plot of the guide aperture against the flow rate, which is compromised by the free play in the guide's drive system. At the same time, the aerodynamic characteristics of the blast heaters are changing, both in the short term (2–4 h) on account of heating and in the long term on account of encrustation of the packing, its melting, shrinkage of the brick, combustion-chamber leakage, and so on.

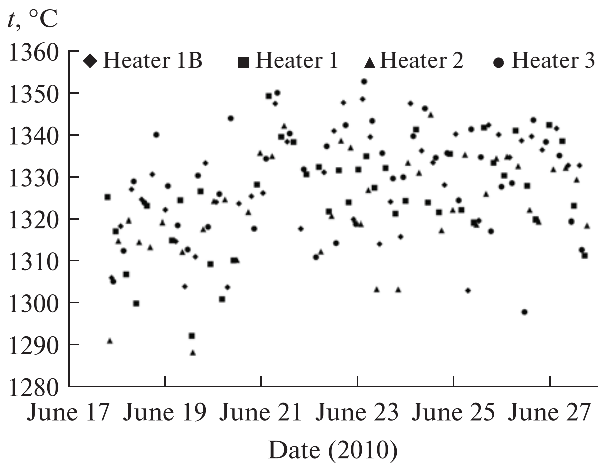


**Fig. 3.** Cupola temperature at the end of the gas period.

Analysis of the readings of stationary instruments indicates that the flow rate of the blast-furnace gas is reduced by 4–6% by the end of the gas period, on account of heating of the packing and increase in its aerodynamic drag, with the same position of the gas choke. Because the aerodynamic characteristics of particular sections of the system will be different for gas and air, the decrease in air flow rate is not proportional to the gas flow rate. The air excess changes accordingly, with further reduction in the final cupola temperature.

The following monitoring results were obtained on July 8, 2010 (when the temperature of the air needed for combustion was 31°C):

| | Heater 1 | Heater 3 |
|---|---|---|
| Pressure ahead of burner, mm $H_2O$ | 240 | 200 |
| Flow rate, $nm^3/h$; | | |
| air | 47396 | 51257 |
| gas | 55000 | 59700 |
| Gas/air ratio | 0.8618 | 0.8786 |

The data presented for the gas flow rate are readings from stationary instruments.

Results from a Chromel–Alumel thermocouple, a thermometer, a measuring tube (designed by the Russian Thermal-Engineering Institute), and a differential manometer show that, at the instant of observation, the air excess $\alpha = 1.18–1.19$, which corresponds to a gas/air ratio of 0.86. The combustion of blast-furnace gas with $\alpha = 1.05$ would permit approximately 55°C increase in the maximum cupola temperature within the gas period.

On account of the fluctuations in the calorific value of blast-furnace gas and the nonoptimal gas/air ratio (the errors in the regulation of fuel combustion), the maximum cupola temperature at the end of the gas period varies from 45 to 56°C at different heaters (Fig. 3).

The mean temperature at the end of the gas period for heater 4 in the system is 1327°C. the cupola temperature at the end of the gas period (°C) is as follows:

| | Heater 1B | Heatr 1 | Heatr 2 | Heatr 3 | Mean for the system |
|---|---|---|---|---|---|
| $t_{min}$ | 1303 | 1293 | 1289 | 1298 | 1296 |
| $t_{max}$ | 1348 | 1349 | 1345 | 1353 | 1349 |
| $t_{me}$ | 1329 | 1325 | 1323 | 1329 | 1327 |
| $\Delta t = t_{max} - t_{min}$ | 45 | 56 | 56 | 55 | 53 |

By equalizing the cupola temperature at the end of the gas period and reducing its fluctuation from cycle to cycle, the temperature of the gas blast may be raised.

In pairwise parallel operation, when two heaters are simultaneously in the gas, the difference in cupola temperatures due to the different gas/air ratios of the simultaneously operating heaters and hence the nonoptimal air excess required for combustion of the blast-furnace gas of the current composition may be assessed. For example, we see in Fig. 4 that the difference in cupola temperatures for heaters 1 and 2 in the gas period is 40°C at 2:40 pm on June 18, 2010. This indicates different gas/air ratios at those heaters. Overall, the difference in the cupola temperature (°C) at the end of the gas period for the pairs of blast heaters is as follows (see also Fig. 5):

| | Heaters 1B and 3 | Heaters 1 and 2 | Heaters 2 and 1B | Heaters 3 and 1 | Mean for the system |
|---|---|---|---|---|---|
| $t_{min}$ | 0 | 0 | 0 | 1 | 0 |
| $t_{max}$ | 33 | 40 | 28 | 35 | 34 |
| $t_{me}$ | 8 | 13 | 9 | 12 | 11 |
| $\Delta t_{max} - \Delta t_{min}$ | 33 | 40 | 28 | 34 | 34 |

The considerable fluctuation in calorific value of the blast-furnace gas (up to 44%) requires continuous correction of the gas/air ratio so as to maintain the maximum cupola temperature. Such automatic correction is possible when using an efficient automatic control system, with the introduction of an optimal control subsystem in which the optimal gas/air ratio in terms of maximum cupola temperature is determined and automatically maintained. The mean increase in cupola temperature in that case is at least 11°C, with a corresponding increase of 9.14°C in the blast temperature.

Thus, by maximizing the fuel-combustion temperature, the cupola temperature in the gas period may be increased by 30–40°C, which is equivalent to 25–33°C increase in the blast temperature.

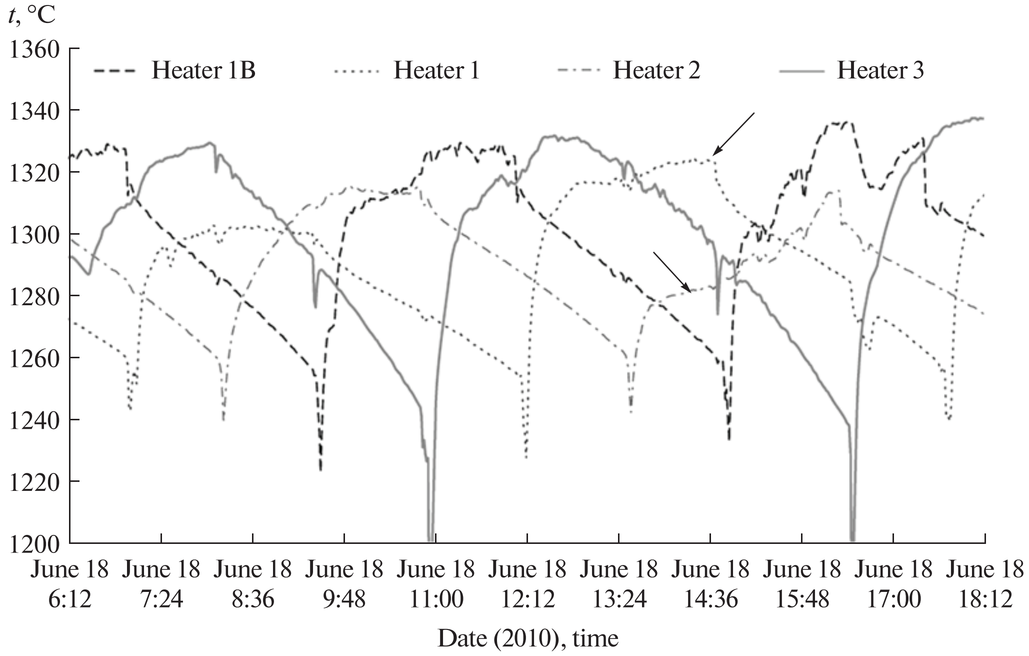


**Fig. 4.** Cupola temperature in blast heater on June 18, 2010.

## MAXIMUM TEMPERATURE WITHIN THE BLAST HEATER

There is significant scope for increasing the blast temperature by boosting the temperature within the heater. Between June 17 and 27, 2010, the maximum gas temperature within the heater in the gas period was 307–425°C in different heaters (Fig. 6). Operation at temperatures below the limiting value (400°C) reduces the blast temperature. Above 400°C, the heater life is reduced.

The temperature (°C) within the heaters (the maximum over the cycle) is as follows:

| | Heater 1B | Heater 1 | Heater 2 | Heater 3 | Mean for the system |
|---|---|---|---|---|---|
| $t_{min}$ | 331 | 333 | 307 | 311 | 321 |
| $t_{max}$ | 425 | 420 | 418 | 409 | 418 |
| $t_{me}$ | 386 | 395 | 380 | 382 | 386 |
| $\Delta t = t_{max} - t_{min}$ | 94 | 87 | 111 | 98 | 97 |

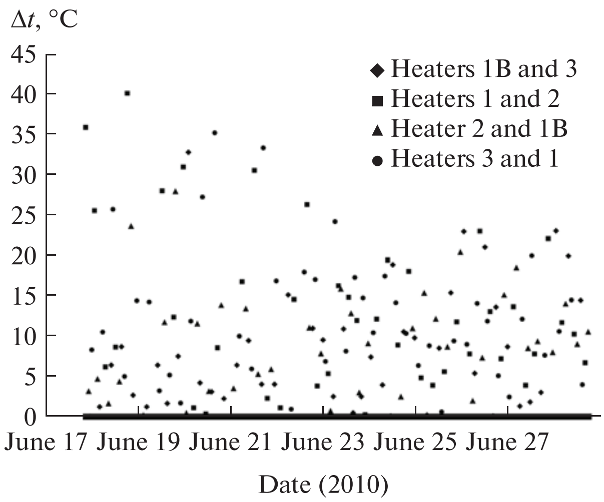


**Fig. 5.** Difference in the cupola temperatures for different pairs of blast heaters operating with gas (at the end of the gas period of one heater).

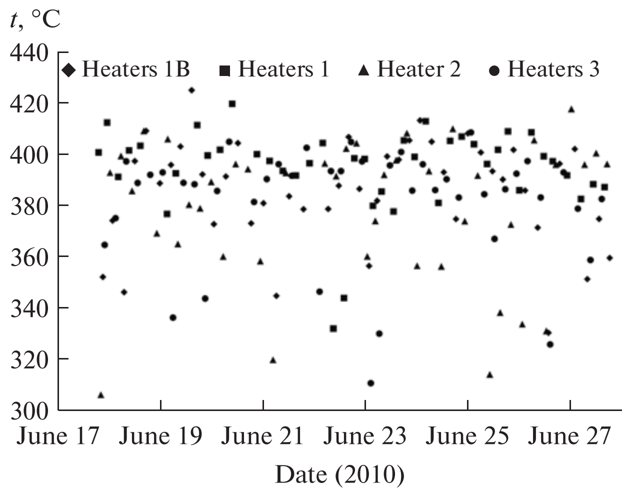


**Fig. 6.** Exhaust-gas temperature within the heater at the end of the gas period.

Numerical experiments by means of the OAO VNIIMT model for furnace 1 at OAO ChMK show that, if the maximum temperature within the heater is 400°C, rather than 380°C, the blast temperature may be increased by 11°C. Note that, between June 17 and 27, 2010, the blast temperature at the end of the gas period fell below 350°C most often (six times) for heaters 2 and 3. This is associated with insufficient automation and possibly with higher aerodynamic drag and insufficient thermal power of the burners.

The optimal control subsystem permits reduction in the temperature fluctuations within the heater and increase in blast temperature, thanks to continuous determination (in on-line mode) of the quantity of combustion products in the gas period that must be supplied to the heater so as to ensure the limiting temperature of 400°C within the heater at the end of the gas period, taking account of the current conditions in the specific heater and in the blast-heater system as a whole.

At present, however, the gas flow rate may only be changed in fixed increments. Analysis of the readings of stationary instruments indicates that, on the basis of the heating rate of the packing, which is monitored in terms of the temperature within the heater, the operator adjusts the gas and air flow rates and hence the flow rate of combustion products filtering through the packing. In particular, the following characteristics are recorded: when the heating of the packing is insufficient, the increment in the gas flow rate is increased from 39000 to 60000 $m^3$/h (by 50%); when the packing is too hot, the increment is reduced from 50000 to 40000 $m^3$/h (by 20%). In the first case, the flow rate first increases and then declines. In the second, the flow rate falls from 53000 to 40000 $m^3$/h, and then rises again to 53000 $m^3$/h (by 25%).

## CUPOLA TEMPERATURE AT THE END OF THE BLAST PERIOD

The following data are obtained for the cupola temperature (°C) at the end of the blast period (see also Fig. 7):

| | Heater 1B | Heater 1 | Heater 2 | Heater 3 | Mean for the system |
|---|---|---|---|---|---|
| $t_{min}$ | 1240 | 1237 | 1240 | 1224 | 1235 |
| $t_{max}$ | 1280 | 1287 | 1292 | 1294 | 1288 |
| $t_{me}$ | 1258 | 1266 | 1268 | 1253 | 1261 |
| $\Delta t = t_{max} - t_{min}$ | 40 | 50 | 52 | 70 | 53 |

Analysis of these data shows that the cupola temperature fluctuates from 1224 to 1294°C for different heaters between June 17 and 27, 2010. The lowest minimum temperature is observed for heater 3: 1224°C, as against 1237–1240°C. Heater 3 also has the largest maximum temperature: 1294°C, as against 1280–1292°C. For the given period, the cupola temperature in heater 3 falls below 1240°C eight times, as against once in heater 1; there are no such incidents in heaters 1B and 2.

Thus, at the end of the blast period, the temperature is 5–15°C lower in heater 3: 1253°C, as against 1258–1268°C. This may be associated with a less efficient heating surface, smaller heat supply in the gas period, greater blast through heater 3 in pairwise parallel operation with heaters 1 and 1B, or other factors.

The installation of flow meters for the cold blast supplied to each heater permits more effective diagnostics of their condition in pairwise parallel operation. The installation of individual blast regulators at each heater permits more effective control of the hot-blast temperature as a result of optimal blast distribution between the cold (earlier in the blast) and hot (later in the blast) air heaters.

The characteristics of the blast periods are as follows:

| | Difference in cupola temperature at the beginning and end of period, °C | Length of period, min | Rate of decline in cupola temperature during period, °C/min |
|---|---|---|---|
| | Heater 1B | | |
| $t_{min}$ | 41 | 106 | 0.25 |
| $t_{max}$ | 83 | 206 | 0.47 |
| $t_{me}$ | 56 | 157 | 0.36 |
| $\Delta t = t_{max} - t_{min}$ | 42 | 100 | 0.23 |
| | Heater 1 | | |
| $t_{min}$ | 28 | 74 | 0.23 |
| $t_{max}$ | 75 | 208 | 0.41 |
| $t_{me}$ | 48 | 153 | 0.31 |
| $\Delta t = t_{max} - t_{min}$ | 47 | 134 | 0.18 |
| | Heater 2 | | |
| $t_{min}$ | 25 | 94 | 0.20 |
| $t_{max}$ | 74 | 181 | 0.41 |
| $t_{me}$ | 47 | 152 | 0.31 |
| $\Delta t = t_{max} - t_{min}$ | 49 | 87 | 0.21 |
| | Heater 3 | | |
| $t_{min}$ | 34 | 99 | 0.31 |
| $t_{max}$ | 106 | 208 | 0.60 |
| $t_{me}$ | 70 | 150 | 0.46 |
| $\Delta t = t_{max} - t_{min}$ | 72 | 109 | 0.29 |

Note that the mean rate of decline in the cupola temperature over the blast period is greatest for heater

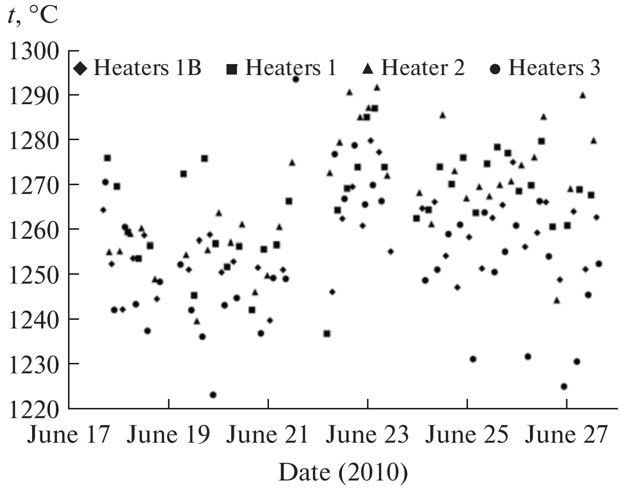


**Fig. 7.** Minimum cupola temperature at the end of the blast period.

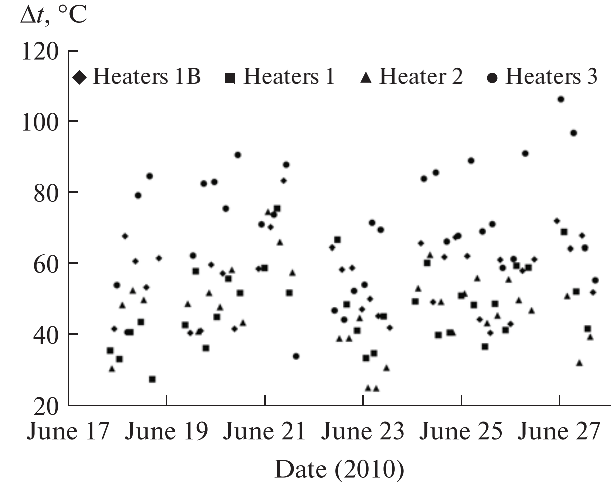


**Fig. 8.** Difference in the temperatures at the beginning and end of the blast period.

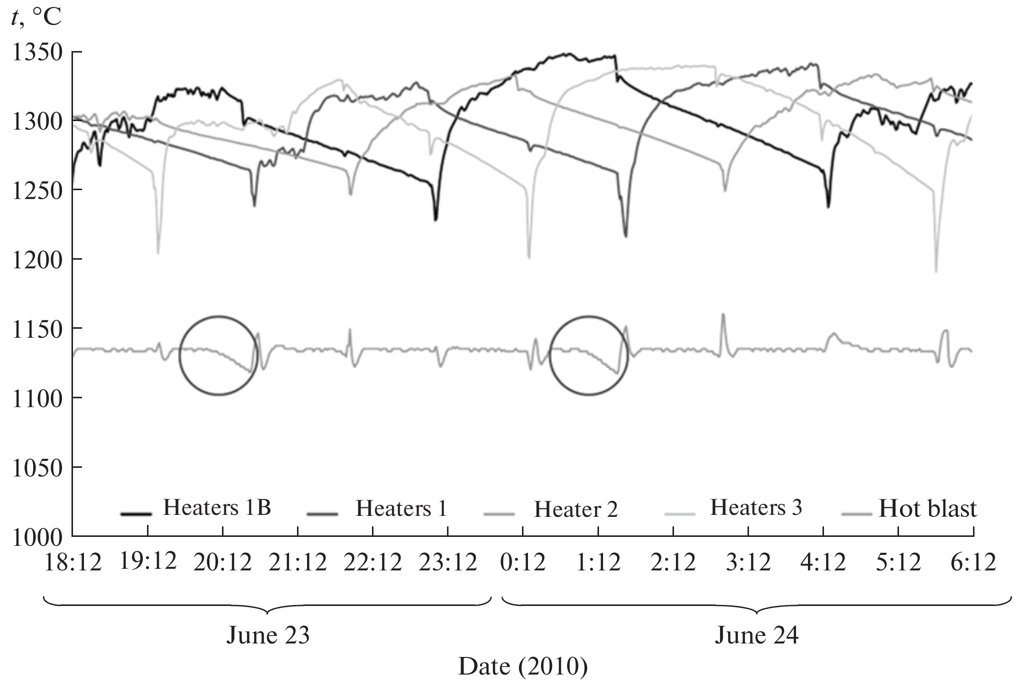


**Fig. 9.** Cupola temperature and hot-blast temperature.

3: 0.46°C/min, as against 0.36°C/min for heater 1B and 0.31°C/min for heaters 2 and 3 (Fig. 8). The mean blast period is 150–157 min, although the difference between the minimum and maximum values for an individual heater may be as much as 134 min (for heater 1). The maximum drop in cupola temperature during the blast period is seen for heater 3: 106°C, as against 74–83°C. The mean temperature drop is 70°C for heater 3, as against 56, 48, and 47°C for heaters 1B, 1, and 2, respectively.

## ANALYSIS OF HOT-BLAST TEMPERATURE

Although the lowest cupola temperature at the end of the blast period is seen for heater 3, its operation leads to practically no drop in blast temperature (Fig. 9). Heater 1 has a more significant influence on the blast. At the end of the blast period for heaters 1 and 2, the blast temperature falls from 1133 to 1121°C, from 1135 to 1112°C, from 1126 to 1096°C, and from 1139 to 1104°C—that is, by 12–35°C. This may be associated with parasitic leakage of cold blast from the combustion chamber into the hot-blast channel. This cold blast bypasses the packing and the cupola thermocouple, whose readings are largely unchanged as a result. The main characteristics of the hot blast between June 17 and 27, 2010 are as follows (min–max/mean): hot-blast temperature (°C) 988–1172/1117; blast flow rate ($m^3$/min) 3164–3917/3478.

## RESULTS OF THERMAL OPTIMIZATION

Thermal analysis suggests the following improvements in operational efficiency of the blast-heater system at blast furnace 1 on the basis of an efficient automatic control system with an optimal control subsystem:

—maximization of the cupola temperature in the gas period, despite the fluctuations in chemical composition of the blast-furnace gas and the gas/air ratio;

—stabilization of the gas/air ratio with fluctuations in gas composition;

—maximization of the hot-blast temperature by determining the optimal operating conditions of each air heater;

—determination of the optimal combustion-product flow rate and its correction so as to attain the limiting temperature within the heater chamber at the end of the gas period;

—indirect measurement of parameters including the temperature field in the heater packing in different operating conditions, the heater efficiency, and the incidence of harmful leaks from the combustion chamber.

This calls for measurements of the following variables.

1. The flow rate of air for combustion—for example, by means of pneumometric tubes produced at OAO VNIIMT. That permits stabilization of the gas/air ratio so as to maximize the cupola temperature.

2. The cold-blast flow rate at each heater, since measurement of this parameter, together with the total flow rate, permits the formulation of the thermal balance for each heater individually and more reliable diagnostics of their operation.

3. The hot-blast temperature at the heater exit (in the hot-blast line);

4. The air and gas pressure at the burner.

5. The pressure in the flue.

6. The hot-blast temperature at the mixer.

Analysis of the operation of the blast-heater system at blast furnace 1 reveals considerable scope for raising the blast temperature and boosting blast-heater efficiency, thanks to the following deficiencies.

1. The lack of automatic parameter regulation in the gas and blast periods. The operator stabilizes the parameters manually.

2. The considerable fluctuations in the chemical composition and hence the calorific value of the blast-furnace gas (by 44%).

3. The large difference in cupola temperature (up to 40°C) of heaters operating simultaneously in the gas period, on account of the different values of the air excess $\alpha$.

4. The considerable fluctuations in the temperature within the heater chamber at the end of the gas period (>90°C).

5. The different drop in hot-blast temperature at different heaters. This permits determination of the optimal blast duration for a particular heater in terms of maximum blast temperature.

6. The large drop in hot-blast temperature (12–35°C) observed in the operation of heater 1. This may be associated with greater parasitic leakage of cold blast from the combustion chamber into the hot-blast channel (short circuiting).

The introduction of an automatic control system an optimal control subsystem developed by OAO VNIIMT permits increase in hot-blast temperature by 30–40°C, with minimum costs. That corresponds to savings in coke purchases of 53–70 million rub/yr.

## CONCLUSIONS

1. A method of thermal analysis has been developed for the air heaters at blast furnaces. This method may be used to establish the scope for raising the blast temperature.

2. Thermal analysis indicates that the hot-blast temperature may be increased by at least 30–40°C on improving the automatic control system and introducing an optimal control subsystem designed by OAO VNIIMT.

3. This approach has been adopted in the overhaul of the air heater at blast furnace 1 at OAO Chelyabin- 2
skii Metallurgicheskii Kombinat. 3

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SPELL: 1. thermophysical, 2. Chelyabinskii, 3. Metallurgicheskii