

Evaluation of the Energy Effect from Heating Blast Furnace Gas before Top-pressure Recovery Turbines at Metallurgical Plants

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Annotation. The article examines a circuit for heating blast furnace gas before gas turbines at metallurgical plants. A methodology is presented for assessing the complex energy effect from the use of fuel energy for generating electricity, taking into account the effect of heating on gas turbines and on the efficiency of the steam-turbine cycle. It is shown that gas heating allows increasing the power of gas turbines and also reducing fuel consumption in the steam-turbine cycle, which will reduce the specific fuel consumption for electricity generation.

Key words: gas recovery compressor-free turbines, blast furnace gas, metallurgical enterprise

Introduction

At modern metallurgical plants, about half of the need for energy of various types is covered by secondary energy resources. Increasing the efficiency of using secondary energy resources is a pressing challenge, as it allows saving primary energy resources. In the papers [1-6] options for using the pressure energy of gaseous fuels at an enterprise are considered.

In metallurgical plants, when producing iron in blast furnaces, there is blast furnace gas formed in large quantities. Currently, most metallurgical plants use blast furnace gas as the main component of the fuel mixture (more than 95 percent by volume), which is burned in boilers at the plant's own CHPs (cogeneration heat and power plants). Another component of fuel is natural gas, which is currently difficult to completely abandon, since it allows avoiding a situation with the fuel cutoff during an emergency shutdown of the blast furnace [7-12]. To more fully utilize the energy potential of blast furnace gas, enterprises install gas turbines called TPRT (top-pressure recovery turbines) upstream the boilers instead of a throttle device. Blast furnace gas enters such turbines with excess pressure, where it expands with a pressure drop to a value slightly higher than atmospheric pressure. An electric generator is connected to the turbine, in which the useful work of gas expansion is converted into electrical energy [8-15]. The use of TPRT (top-pressure recovery turbines) allows generating additional amounts of electricity only by using the potential energy of excess blast furnace gas pressure. The disadvantage of this circuit is the decrease in the temperature of the fuel entering the boiler due to the blast furnace gas cooling during expansion in the turbine, which reduces the heat amount supplied to the steam-turbine cycle.

One of the ways to solve this problem is to preheat the blast furnace gas before the TPRT, which will increase the TPRT power output and also reduce fuel consumption in boilers by increasing the physical heat of the introduced fuel. To conduct a feasibility study of this option, it is necessary to have a methodology for assessing the energy effect from the use of gas heating.

The purpose of this article is a comprehensive assessment of the energy effect from the use of blast furnace gas heating before the TPRT (top-pressure recovery turbines), taking into account the effect of blast furnace gas heating on both the gas turbine operation and the steam-turbine cycle efficiency.

Methodology for assessing energy efficiency from the use of blast furnace gas heating

The gas coming from the blast furnaces is cleaned of dust and then it passes through the TPRT (top-pressure recovery turbines).

The power generated by the TPRT will be calculated using the formula:

$$N_{TPRT} = G_{b.f.g.} \cdot c_{b.f.g.} \cdot T_{g.in.} \cdot \left[1 - \left(\frac{P_{g.out.}}{P_{g.in.}} \right)^{\frac{k-1}{k}} \right] \cdot \eta_{g.t.} \cdot \eta_{el}, (1)$$

where N_{TPRT} – TPRT power, W; $G_{b.f.g.}$ – blast furnace gas consumption, m³/s; $T_{g.in.}$ – gas inlet temperature, K; $P_{g.in.}$, $P_{g.out.}$ – inlet and outlet gas pressures, respectively, Pa; $c_{b.f.g.}$ – isobaric volumetric heat capacity of gas, J/(m³ K); k – heat capacity ratio; $\eta_{g.t.}$ – internal efficiency ratio of a gas turbine; η_{el} – electromechanical efficiency of a gas turbine.

From formula (1) it follows that the gas turbine power is proportional to the value of the thermodynamic temperature of the gas upstream the gas turbine.

Then the gas turbine capacity in the presence of gas heating can be determined from the dependence:

$$N_{TPRT.h.} = N_{TPRT.w.h.} \cdot \frac{T_{TPRT.h.}}{T_{TPRT.w.h.}}, (2)$$

where $N_{TPRT.h.}$, $N_{TPRT.w.h.}$ – the TPRT power for the circuit with and without gas heating, respectively, W; $t_{in.h.}$, $t_{in.w.h.}$ – gas temperatures at the inlet to the gas turbine for the circuit with and without heating, respectively, K.

The actual temperature of the gas at the turbine outlet can be determined using the formula:

$$T_{out} = T_{in} \cdot \left[1 - \left(1 - \left(\frac{P_{g.out.}}{P_{g.in.}} \right)^{\frac{k-1}{k}} \right) \cdot \eta_{en.} \right], (3)$$

Increasing the blast furnace gas temperature allows for a reduction in fuel consumption, provided that the amount of usefully transferred heat in the boiler and the steam-turbine cycle power remain unchanged. The temperature at the outlet of the TPRT, calculated using formula (3), is equal to the temperature of the blast furnace gas at the boiler inlet.

The consumption of the fuel mixture entering the boiler in the presence of blast furnace gas heating before the TPRT is determined by the formula:

$$B_h = B_{w.h.} \cdot \frac{Q_L^W + r_{b.f.g.} \cdot c_{b.f.g.} \cdot t_{w.h.} + r_{n.g.} \cdot c_{n.g.} \cdot t_{n.g.} - V_{o.g.} \cdot c_{o.g.} \cdot t_{o.g.}}{Q_L^W + r_{b.f.g.} \cdot c_{b.f.g.} \cdot t_h + r_{n.g.} \cdot c_{n.g.} \cdot t_{n.g.} - V_{o.g.} \cdot c_{o.g.} \cdot t_{o.g.}}, (4)$$

where B_h , $B_{w.h.}$ – fuel consumption for circuits with and without gas heating, respectively, m³/s; Q_L^W – calorific value of fuel, J/m³; $r_{b.f.g.}$, $r_{n.g.}$ – volume fractions of blast furnace and natural gas in fuel, respectively; $t_{b.f.c.w.h.}$, $t_{b.f.c.h.}$, $t_{n.g.}$, $t_{o.g.}$ – temperatures at the inlet to the burners of the blast furnace gas boiler for circuits without and with heating of natural gas, the temperature of the gases leaving the boiler, respectively, °C; $c_{b.f.g.}$, $c_{n.g.}$, $c_{o.g.}$ – isobaric volumetric heat capacities of blast furnace, natural and exhaust gases, respectively, J/(m³ K); $V_{o.g.}$ – specific air consumption for combustion of 1 m³ of fuel, m³/m³.

Let us introduce a criterion that determines the relative efficiency of the heating organizing. The specific fuel consumption for generating a unit of electricity can be taken as such a criterion.

The specific fuel consumption for using the TPRT will be determined by the formula:

$$b = \frac{N_{s.t.} + N_{TPRT}}{B} (5)$$

where $N_{s.t.}$, N_{TPRT} – the power of a steam-turbine cycle and the TPRT power, respectively, W; B – fuel consumption in the steam-turbine cycle, m³/s.

This criterion allows us to evaluate the efficiency of using fuel energy to generate electrical power.

Calculation of the energy effect from the use of blast furnace gas heating

Let's consider a CHP (cogeneration heat and power plant) of a metallurgical enterprise. We assume that 50% of blast furnace gas production goes to the CHP. Total consumption of blast furnace gas is 1,188 thousand m³/h, natural gas 62.52 thousand m³/h. The composition of the fuel mixture is 95% of blast furnace gas, 5% of natural gas. Blast furnace gas composition: CO=30%, CO₂=20%, N₂=50%. Natural gas composition: CO=97%, CO₂=2%, N₂=1%. The electrical power generation at the CHP is 450 MW, which corresponds to thermal efficiency of 30% at generator terminals. The blast furnace gas temperature after gas cleaning is 60°C, absolute pressure is 3 bars. Natural gas temperature is 20°C. The excess air factor is 1.1. As a heat source, we can use the exhaust gases from the hot blast stove, the temperature of which we will take as 350°C. We will limit the heating of blast furnace gas to 150°C.

According to formulas (1) - (5), there were calculations carried out for circuits with gas heating and without heating. The capacity of the TPRT, determined by formula (1), increases from 30.13 MW to 38.28 MW, i.e. it will increase by 27%; the total electricity generation at the combined heat and power plant increases from 480.13 MW to 488.28 MW, i.e. it will increase by 1.7%. Fuel consumption drops from 1250.52 thousand m³/h to 1226.2 thousand m³/h, which corresponds to the decrease of 2%. The specific fuel consumption for electricity generation decreases from 2.63 m³/(kW h) to 2.54 m³/(kW h), i.e. decreases by 3.5%.

The reduction in specific fuel consumption is explained by two reasons. The first of these is the TPRT power output increase by the inlet temperature rise. The second reason is the fuel consumption reduction in the steam-turbine cycle due to the increase in the temperature of the blast furnace gas entering the boiler. Reducing the blast furnace gas consumption when there is an excess of it does not provide any economic effect, but it can provide an effect when there is a shortage of blast furnace gas at a metallurgical plant. However, in addition to blast furnace gas, the fuel also contains natural gas, the reduction in consumption of which provides an economic effect.

Conclusions

The article analyzes the energy effect of using blast furnace gas preheating upstream the TPRT at metallurgical plants. The example considered shows that heating increases the TPRT capacity by 27% due to an increase in the inlet gas temperature, which corresponds to an overall increase in power generation at the CHP by 1.7%. It was also noted that, compared to the circuit with a TPRT without heating, with the same generation of electricity from the steam-turbine cycle, it is possible to reduce the fuel mixture consumption by 2% due to an increase in the sensible heat introduced into the boiler with fuel. The use of a circuit with blast furnace gas heating allows for a reduction in specific fuel consumption by 3.5% both by increasing the total generation of electrical power and by reducing fuel consumption at the CHP.

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