Primary diagnosis of energy efficiency in an integrated steel plant, based on intensive energy-saving methodology. Part 1

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The energy efficiency of the integrated steel plant is studied basing on the Intensive Energy Conservation Methodology. The primary diagnostics of the energy efficiency of the integrated steel plant is carried out.
The boundaries of the object of study are established from iron ore deposits to the finished steel cold-rolled sheet. The research object is presented in the form of a directed graph, and the flows of materials in this network are calculated. The thermophysical heat absorption of materials and intermediates within the boundaries of a closed heat engineering complex has been estimated. The energy intensity of the cold-rolled steel sheet within the same boundaries has been calculated.
Efficiency of production was estimated by comparing heat consumption and energy intensity. The complete intensive energy conservation reserve in the complex has been determined. Reserve structure is studied and directions of its implementation are discussed. It is shown that the most complete implementation of the energy-saving reserve is possible only with the transition of a new generation of steel engineering and technology.
Key words: energy efficiency, integrated steel plant, intensive energy saving methodology, graph theory, network flows.
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Introduction

Diagnostics of energy efficiency is of great importance for the steel industry due to the very large economic scale of steel production in the world — more than 1.5 billion tons per year. At the same time, the production of 1 ton of steel requires a total energy expenditure of all types over 1 ton of standard fuel (coal equivalent).

These circumstances determine the extreme relevance of the energy efficiency diagnostics of the steel industry to determine a possible decrease of energy costs for production [1–4].

In the production of rolled steel from ores, almost all materials are heat treated. Thus, the production of rolled ferrous metals from iron ores is a classic thermal, or heat technology.

Integrated steel plant contains typical mandatory elements in typical relationships: the production of iron ore concentrate, the production of pellets and sinter, blast furnace (BF) production of cast iron, steel making of possible three types: the open hearth furnace (OHF), or the basic oxygen furnace (BOF) or the electric arc furnace (EAF), production of hot-rolled sheet, and production of cold-rolled sheet.

In this paper, for the sake of definiteness of the analysis, a cold-rolled steel sheet was accepted as the leading, most demanded final product of the metallurgical plant.

The set of elements and their connections of the metallurgical plant is a topologically complex object that can be adequately displayed by a directed graph. Further, for brevity, this graph, reflecting the main connections of the metallurgical plant, will be called the "object" of this research.

The main energy characteristics of this object are the apparent energy consumption of all types of energy carriers: fuel, air, water. Besides, converted energy agents are also consumed: hot water, steam, electricity, air separation products that are produced using commercial fuel and contain these energy costs in a hidden form.

In addition, the object consumes both materials and products of external production: ferroalloys, lime, pellets, ores, ore concentrates and others, which also contain hidden energy consumption of primary fuel. The total, final, integral indicator of total energy consumption per unit of final product is energy intensity.

To evaluate this quantity, it is necessary to compare it with a certain reference value, which can be taken as heat consumption, physical heat absorption, and thermophysical justified consumption of heat energy for the production of this product, which does not depend on energy supply options, but is determined only by the thermophysical properties of materials subjected to heat treatment. Moreover, the total heat consumption depends not only on the energy of the process itself, but also on the proportion of this process in the final product. So, for example, the proportion of coking processes in the final sheet does not exceed 0.5.

Similar values in the object are determined by the differential coefficients of the mass flows "input / output" in each process and the integral end-to-end coefficients per final sheet. Diagnostics of energy efficiency can be represented by at least two components: a reserve of energy conservation and heat consumption (theoretical minimum energy cost) for production. In turn, the energy conservation reserve can be defined as the difference between the energy intensity of a product and its heat consumption (theoretical minimum energy consumption). The steel integrated plant is the subject of close attention and research in various aspects.

In the paper [5] of 1974, Giftopoulos E. P. et. al., proposed, as a measure of the efficiency of industrial processes, to take the ratio of the difference between the available useful work of finished products, and raw materials, to the available useful work of consumed fuel [5].

Taking into account the weighted content of iron oxides in the starting materials, this difference amounted to $6 \cdot 10^6$ Btu/t (6,330 MJ/t = 216 kgce/t), and it was stated as the value of the theoretical minimum energy for the conversion of the starting materials into the final product. Actual fuel energy expenditures calculated according to the data of 1969 amounted to $28.6 10^6$ Btu/t (30.173 GJ/t = 1,029 kgce/t) attributed to crude steel. The overall steel production energy efficiency, equal to the ratio of these two values, was thus 21 %. Based on these calculated data, it was concluded that there are significant opportunities for fuel conservation in the steel industry [5].

M. H. Chiogioji, presented efficiency in steel industry from 39 to 42 %; theoretical minimum energy consumption for steel production is 0.239 kgce/t [6]. All submitted results relate to the production of crude steel only and do not extend to the finished cold rolling. One of the other approaches uses pinch analyses (Martin McBrien and al. [7]) to solve this problem.

In that paper, the method of pinch analysis is used to estimate the potential for energy savings through heat recovery across all processes in the primary steel supply chain. As a result, process heat recovery may save approximately 1.8 GJ/t of hot rolled sheet (GJ/t hrs), integrated heat recovery with conventional heat exchange could save 2.5 GJ/t hrs, and an alternative heat exchange that also recovers energy from hot steel could save 3.0 GJ/t hrs.

J. De Beer et. al. [8] performed an analysis of the possibilities of decreasing the specific energy consumption for the production of hot-rolled sheet along three routes: blast-furnace production, direct reduction and melting of scrap. In total, energy consumption can be reduced from the current 19 GJ/t of crude steel to 12.5 GJ/t, indicating specific existing energy-saving technologies, including direct reduction of iron and near-net-shape casting techniques. This energy saving reserve is thus 6.5 GJ/t of crude steel.

In [9] it is indicated that energy consumption in steel industry can be reduced, according to various sources, from 15 to 22 %, provided that proven technologies and technical solutions are applied. Fruehan [10] presents the results of calculations of the minimum energy consumption for each intermediate process that constitutes the technological chain of production of rolled steel, including cold rolled.

The final comparison of the actual and minimum energy costs includes separately:

- pig iron production 13–14 and 9.8 MJ/t;
- production of BOF steel 10.5–11.5 and 9.8 MJ/t;
- hot-rolled sheet 2.0–2.4 and 0.03 MJ/t;
- cold rolled sheet 1.0–1.4 and 0.02 MJ/t.

The energy conservation reserve in these separate technological stages can be:

- pig iron production 25–30 %;
- production of BOF steel 25–31 %;
- hot rolled sheet 99 %;
- cold rolled sheet 98–99 %.

However, the article does not contain information about the full, end-to-end reserve of energy saving in the interval from iron ore deposit to cold-rolled sheet in a single economic complex, which only has practical significance for the enterprise.

In this paper, the task is to determine the full, integral reserve of energy conservation in a closed heat production complex for the production of cold rolled steel sheet from iron ore during the primary diagnosis, using the algorithms of the of Intensive Energy Saving Methodology (IESM) [11–13], developed in the 80–90ies of the 20th century by professor A. Klyuchnikov at the Moscow Power Engineering Institute.

In the first part of the work, the boundaries of the research object are determined, which is represented in the form of a directed graph, and the end-to-end flow rates of raw materials and semi-finished products are calculated for the production of the final product — cold-rolled steel sheet.

These data are necessary for subsequent analysis, namely: to determine the physically determined heat absorption of the processed materials and the energy intensity of the resulting products, as well as to diagnose energy efficiency and determine the full reserve of energy savings. The results are planned to be presented in the next article.

Research methodology

The complete intensive energy conservation reserve is defined as the difference between energy intensity and heat consumption. The ratio of heat consumption/energy intensity determines the overall energy efficiency in the production complex of the iron and steel industry. The consequent application of the IESM involves the formation of the structure and boundaries of the studied object from natural resource deposits to the finished product warehouse.

The modern integrated steel plant uses iron ore, coking and steam coal, natural gas, open water and atmospheric air. Iron ores go through the stage of enrichment and production of iron ore concentrate. In most cases, the enrichment stage does not contain heat treatment of iron ores. But for some ores (for example siderite), firing-magnetic enrichment is used.

Further, the iron ore concentrate is agglomerated to obtain both pellets and sinter. Coking coals are used for the production of coke, while steam coals are also partially used. Natural gas and steam coal are used for the production of electric energy in the district electric system and at the electric power stations of the enterprise. Natural gas also goes directly to the plant for use in blast furnace production and in heating and thermal furnaces.

The object of this study, in accordance with the IESM, is a closed heat engineering complex of an integrated steel plant, covering the interval from finished products to iron ore deposits. The objective of the study is to estimate the energy efficiency of the processing of iron ores into cold-rolled steel sheet, as well as the assessment of the most complete energy-saving reserve in the object.

Defining essential concepts

In accordance with the IESM, the energy efficiency of the complex can be defined as

$$\eta_1 = Q/E \qquad (1)$$

where Q — heat absorption of the finished product (cold-rolled heat-treated sheet), kgce/t; E — is the energy intensity of the finished product, kgce/t.

A full reserve of energy conservation

$$R = E - Q \qquad (2)$$

where R — the full reserve of energy conservation in a closed heat production complex for the production of finished steel cold-rolled sheet, kgce/t.

Object of study as a graph

The sequence of operations for the production of cold-rolled heat-treated sheet from iron ores is presented in the form of a directed graph, the vertices of which correspond to semiproducts, and the edges correspond to the technological processes of their production.

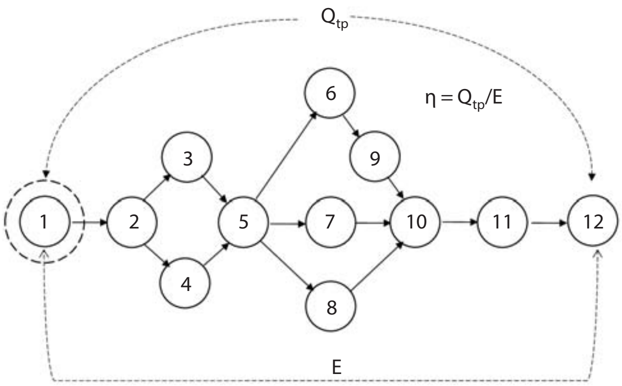

Fig. 1. Object of study as a graph: 1 — Iron ore (in deposit); 2 — Concentrate; 3 — Pellets; 4 — Sinter; 5 – Crude iron; 6 — OHF steel; 7 — BOF steel; 8 — EAF steel; 9 — Ingot, 10 — Slab; 11 — Hot rolled sheet; 12 — Finished, cold rolled sheet; Q_{tp} — the total heat consumption for the final product; E — energy intensity for the final product; η – assessment of the energy efficiency of an object.
(This diagram does not indicate the incoming flows of coke, scrap, ferroalloys, metallized pellets)

The characteristic of this graph begins with a quantitative determination of the mass flows of semiproducts for manufacture of the final product.

For this, real data were used for one of the enterprises, as well as industry-wide data of enterprises of the Russian Federation [12–14].

The specific consumption of incoming semiproducts for manufacture of subsequent products is presented [14] in **Table 1**. (Numbering of semiproducts is in accordance with **Fig. 1**)

The integral (through) coefficients of each material for the final product can be calculated by the expression:

$$K_i = \prod_{N}^{i} k_i \qquad (3)$$

where k_i — differential coefficients, t/t of semiproduct (see Table 1); i — number of technological stage (cold rolling, hot rolling, continuous cast slab etc.); K_i — integral (through) coefficients, t/t of the final product.

Here i takes values only from a subset of the route from N to this stage.

Thus, in the object of study, by differential coefficients in each intermediate production, end-to-end flow coefficients are calculated per final sheet (**Table 2**).

Table 2 in bold indicates the maximum values in each row of the table corresponding to different methods of steel production.

So, the OHF route requires maximum production of liquid steel. This is determined by the significant cutting off the head and tail parts of the ingot rolling out.

Table 1. **Specific consumption of incoming flows per 1 ton of semiproducts (differential coefficients)** [12–14]

No.	Semiproducts	t/t	Incoming mass flows	No.
2	concentrate	2.227	Iron ore	1
3	pellets	1.1167	concentrate	2
4	sinter	0.5509	concentrate	2
5	crude iron	0.798	sinter	4
		0.899	pellets	3
		0.446	*coke*	–
6	OHF steel	0.630	crude iron	5
		0.427	*steel scrap*	–
		0.012	*ferroalloys*	–
7	BOF steel	0.903	crude iron	5
		0.233	*steel scrap*	–
		0.012	*ferroalloys*	
8	EAF steel	0.101	crude iron	5
		0.815	*steel scrap*	–
		0.211	*metallized pellets*	–
		0.042	*ferroalloys*	–
9	ingot	1.042	OHF steel	6
10	slab	1.195	ingot	9
10	slab	1.000	BOF steel	7
10	slab	1.000	EAF steel	8
11	hot rolled sheet	1.037	slab	10
12	finished, cold rolled sheet	1.075	hot rolled sheet	11

Table 2. **Integral (through) coefficients, t/t of the final product**

No.	Intermediate		Steel production routes		
			OHF	BOF	EAF
		Flow coefficients, t/t of semiproducts			
		Diff.	Integral	Integral	Integral
		k_i	K_i	K_i	K_i
1	**Finished cold rolled sheet**	**1.000**	**1.000**	**1.000**	**1.000**
2	Hot rolled sheet	1.075	1.075	1.075	1.075
3	Cold rolled sheet	1.037	1.115	1.115	1.115
4	Slab	1.195	1.332	1.115	1.115
5	Liquid steel	1.042	**1.388**	1.162	1.162
6	Crude iron	0.676	0.938	**1.049**	0.118
7	Steel scrap	0.427	0.593	0.271	**0.947**
8	Sinter	0.789	0.740	0.828	0.093
9	Pellets	0.899	0.844	0.943	0.106
10	Coke	0.446	0.419	0.468	0.053
11	Concentrate (for sinter)	0.551	0.408	0.456	0.051
12	Iron ore (for sinter)	0.327	0.242	0.270	0.030
13	Concentrate (for pellets)	1.117	0.942	1.053	0.118
14	Concentrate (totally)	–	1.350	**1.509**	0.169
15	Iron ore (for concentrate)	2.227	3.006	3.360	0.377
16	Iron ore (totally)	–	3.248	**3.631**	0.408

BOF route requires the largest amount of pig iron, which leads to an increased load on the sinter-coke-BF complex.

EAF route consumes the largest amount of steel scrap: by 1.5–2.5 times more than the rest. This determines the minimum energy intensity of such production due to the low energy intensity of scrap.

The obtained integral flow (through) coefficients are a necessary step for calculating the total heat consumption Q_{tp} in the object.

Conclusions

Thus, the main elements of the methodology of intensive energy saving are applied to the study of the energy efficiency of a generalized integrated steel plant.

The object of research, a complex for processing iron ores into cold-rolled steel sheet, is presented in the form of an oriented graph.

On the basis of the known consumption characteristics of certain technological stages of ferrous metallurgy, the through-flow coefficients of the consumption of raw materials and semi-finished products for the production of the final product (cold-rolled steel sheet) have been calculated.

These data are necessary for subsequent analysis, namely: to determine the physically determined heat absorption of the processed materials and the energy intensity of the resulting product.

Thus, the initial stages of energy efficiency analysis based on the intensive energy saving methodology have been completed. The final results of the analysis are planned to be presented in the next article.

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