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DIRECTIONS AND PROSPECTS OF USING LOW GRADE PROCESS FUEL TO PRODUCE ALUMINA

O.A.DUBOVIKOV, V.N.BRICHKIN
Saint-Petersburg Mining University, Russia

Power consumption across the globe is constantly increasing for a variety of reasons: growing population, industrialization and fast economic growth. The most widespread gaseous fuel – natural gas – has the low production cost. It is 2-3 times cheaper than liquid fuel production and 6-12 times cheaper than coal production. When natural gas is transported to distances from 1.5 to 2.5 thousand km by the pipeline, its cost with account of transportation is 1.5-2 times less than the cost of coal and the fuel storage facilities are not needed. Plants powered by natural gas have the higher efficiency as compared to the plants operating on other types of fuel. They are easier and cheaper to maintain and are relatively simple in automation, thus enhancing safety and improving the production process flow, do not require complicated fuel feeding or ash handling systems. Gas is combusted with a minimum amount of polluting emissions, which adds to better sanitary conditions and environment protection. But due to depletion of major energy resources many experts see the future of the global energy industry in opportunities associated with the use of solid energy carriers. From the environmental perspective solid fuel gasification is a preferred technology. The use of synthetic gas was first offered and then put to mass scale by English mechanical engineer William Murdoch. He discovered a possibility to use gas for illumination by destructive distillation of bituminous coal. After invention of the gas burner by Robert Bunsen, the illumination gas began to be used as a household fuel. The invention of an industrial gas generator by Siemens brothers made it possible to produce a cheaper generator gas which became a fuel for industrial furnaces. As the calorific value of generator gas produced through gasification is relatively low compared to natural gas, the Mining University studied possibilities to use different types of low grade process fuel at the Russian alumina refineries as an alternative to natural gas, access to which is restricted for some of the regions.

Key words: global energetics, coal, black oil, natural gas, low grade process fuel, alumina refineries, generator gas, calorimetric combustion temperature, theoretic combustion temperature.

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According to one of the scenarios developed by the international non-governmental organization (the Roman Club), global resources of raw materials, including energy, will reduce by a factor of three by the middle of the 21st century and the volume of industrial production will go down. The other scenario predicts resources reduction by one-third and the volume of industrial production at the same level as in the beginning of the century [2]. Neither is acceptable for dynamic and sustainable global development of industrial civilization. But these scenarios do not take into account the potential scientific and technological advances in the reduction of energy consumption and the use of alternative energy sources neither do they give due regard to the increasing technological capabilities of the mankind.

It is the technology and not the mineral resources that is the main driver of the scientific and technological progress. The backward technology leading to high production costs impede the spread of progress to the related industrial sectors. Global deficit of electric power is also attributable to the constantly growing output of energy-intensive products. The Eastern Siberia regions of Russia previously renowned for their hydroenergy resources now run short of electric power, as aluminium production is increased at a faster rate than the energetic sector develops. Reduction in consumption of energy in general and of electric energy in particular becomes one of the high priority directions of present-day metallurgy development.

Lack of electric energy entails a growing scarcity of hydrocarbons and metallurgical coke. Conversion of thermal power plants from natural gas to coal is gaining momentum. If new power sources may in future offset the electric energy deficit without any visible changes in its consumption technology, it is impossible to remove coke from the reduction of iron ore raw materials or production of graphitized carbon materials unless technology undergoes fundamental changes.

The problem of gradual depletion of large deposits is quite real in the long run. For instance, the reserves of major power sources, at least those explored and easily extractable using existing technologies, to date according to different estimates are quite scarce, though low rank caustobioliths will last for at least a thousand years (Table 1) [8].

Table 1

Global Reserves of Fossil Fuels, billion tonnes of reference fuel

Natural fuel	Explored reserves		Forecasted reserves	
	minimum	maximum	minimum	maximum
Solids (caustobioliths)	450	830	5,000	12,000
Oil and gas condensate	95	150	220	450
Hydrocarbons in bituminous sands and slates	90	120	370	730
Natural gas	65	100	240	370
Total	700	1,200	5,830	13,550

Possible solutions to this problem are as follows: 1) intensified geological exploration and use of new methods for electric energy production; 2) enhancement of extraction and processing technologies for subsoil resources and industrial raw materials; 3) reduced consumption.

The first solution assuming extensive exploration of material and energetic resources is still applicable, but its limitations as concerns the scarcity of oil and gas resources become more evident. Thus exploration of hard-to-reach hydrocarbon resources becomes inevitable, exposing a need in new gas and oil pipelines. For reasons that are clear the third option will not be chosen either.

The wisdom of researches pursuing enhancement of extraction and processing technologies for natural and industrial resources is a much discussed topic, but actual progress in this direction is unreasonably slow. In 2007 with the support of the government the All-German Congress on International Raw Material Markets was organized and held by the Federal Union of German Industry. Congress participants laid emphasis on the matter that Germany's security of raw materials supply is not confined to stable supply of oil and gas only, it also implies access to metal in-situ reserves, as the vast majority of industrial products offered by Germany at the global market are based on the metal-containing raw materials. And national economy of Germany is entirely dependent on their import and consequently on global raw material markets. By 2020 the overall efficiency of metal raw materials sector is forecasted to be almost doubled. This target is expected to be achieved at least through highly technological optimized use of raw materials and supplies and development of the recycling sector [15].

The economy of these countries - of Germany extremely dependable on the import of raw materials and of Russia almost 100 % reliant on its domestic raw materials - is largely affected by global prices for raw materials. In Russia the situation is more complicated. For Russia these effects are much stronger, as its difficult mining and climatic conditions reduce the competitiveness of the Russian raw materials in the context of an open economy. It becomes unprofitable to export such raw materials and when they are used domestically the issues emerge associated with their cost and profit margin of the final product which is also intended for foreign markets. In view of the above, attention shall be paid to the option of utmost relevance in the present-day economic environment that already in the short turn will be adopted by the countries having less mineral resources than Russia, namely the enhancement of extraction and production technology for mineral raw materials.

Situation at the global market of alumina and aluminum strengthens the need to further reduce energy consumption and cost of produced products in order to increase competitiveness.

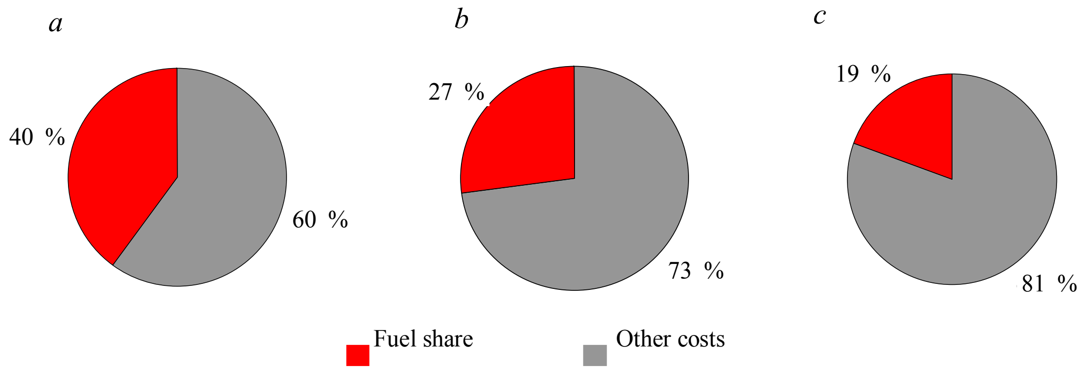
Energy consumption of the best foreign refineries processing high quality bauxites under Bayer's technology is circa 7-8 GJ per 1 ton of alumina, while for Russian refineries dealing with low quality raw materials this indicator is more than 54 GJ/t. The main reason for that is the quality of the used raw materials. If the foreign refineries producing alumina under the Bayer's method use bauxites with 10-12 silicon module and Al_2O_3 concentration of 50-55 %, the nepheline raw material have silicon module of circa 0.65 with Al_2O_3 concentration near 25-26 %.

Of the utmost interest is RUSAL Achinsk OJSC (Achinsk Alumina Refinery) using a unique technology having no parallels in the world to produce alumina from nephelines by sintering. Despite poor quality of raw materials as discussed above, the refinery's proximity to the source of raw materials and to consumers of metallurgical alumina, own CHP plant running on cheap coal and production of by-products make sintering technology not only competitive but bring refinery to one of the top positions in terms of product cost. When sintering technology is used the most energy-intensive part of alumina production process is the attainment of sintering and calcination temperatures [18].

As concerns calcination there are standard proven solutions which can be used [11], but in case with sintering temperature attainment, machines from other industries shall be adapted [16], or existing units shall be grouped into a new combination [14], or technology enhancement options shall be investigated [10].

Replacement and upgrade of sintering units at the operating production facility requires significant financial inflows and long adaptation of machines for the unique technology, which has a negative impact on economic indicators of modernization. One of the ways to reduce costs at the stage of sintering temperature attainment is selection and use of a cheaper fuel. The most prospective is the use of coals of Kansk-Achinsk Basin (KAB) with opencast mining of cheap low-ash brown coals, which is located in the close vicinity of the refinery.

As tentative estimates show conversion to coal fuel will help to reduce the fuel share in the structure of the product cost (please see Figure).



Estimated fuel costs within the alumina production cost: *a* – black oil; *b* – bituminous coal; *c* – brown coal

Coals of Kansk-Achinsk brown coal basin have low calorific value ($Q_{\text{н}}^{\text{р}}$ = 3.5-3.8 Mcal/kg), high humidity ($W^{\text{р}}$ = 33 % or more) and high content of volatile compounds (45-48 %) which creates some challenges for their use as a sintering fuel.

It shall be noted that the challenges associated with the use of KAB brown coals for sintering are specific to Achinsk Alumina Refinery with account of its technological conditions, location and infrastructure. In his time after thorough examination of technological and economical issues of oil refinement, D.I. Mendeleev made a proposal to build refineries in locations where oil products consumption is concentrated.

Conversion to solid fuel except the obvious economic advantages poses some technological challenges. When coal is used, in addition to first-order factors related to combustion performance, the secondary influence on the sintering process through the fuel ash shall be taken into account.

Introduction of a system adjusting feed mixture modules in case of any changes in fuel ash content and structure will allow to a certain extent to stabilize the quality of a sinter [4], and owing to considerable reserves, proximity to potential consumers and relative ease of mining the brown coals can be always reviewed as an alternative source of fuel [1, 5].

Coal gasification is another high-potential technology for using solid energy carriers. The main advantage of solid fuel gasification is low negative impact on the environment. Due to better combustion completeness of gaseous fuel the amount of resultant polluting chemical compounds in evoking fumes and ash residuals is severalfold less and in some cases even by several orders less. This brings savings on expensive equipment for treatment of fume emissions and decontamination of solid secondary wastes.

Due to relatively low calorific value of the generator gas produced through gasification there was a need to study the combustion process of generator gas. It was decided to study a mixed generator gas having the following composition, % of total volume: 5.0 CO_2; 0.3 H_2S; 0.3 C_mH_n; 26.5 CO; 13.5 H_2; 2.3 CH_4; 51.9 N_2; 0.2 O_2 and water content W = 5.7 g/m^3.

Table 2 below shows the main generator gas combustion indicators with the excess air ratio α = 1.10.

Table 2

Calculated generator gas combustion indicators

Indicator	Value
Calorific value $Q^{р}_{н}$, kJ/m^3	5,866
Theoretical air volume L_{theor}, m^3/m^3	1.22
Practical air volume L_{pract}, m^3/m^3	1.35
Resultant gaseous combustion products V_g, m^3/m^3	2.15
Composition of combustion products, % of total volume:	
CO_2	15.92(1 – x)
CO	15.92x
H_2O	9.23(1 – y)
H_2	9.23y
N_2	73.52
O_2	1.19 + 0.5(15.92x + 9.23y)
SO_2	0.14
Density of combustion products ρ, kg/m^3	1.33
Calorific content of combustion products i_0, kJ/m^3 (kkal/m^3)	2,728
Calorimetric temperature of combustion process $t_к$, °C obtained through calculation	1,646
Dissociation rate of carbon dioxide x	0
Dissociation rate of water vapour y	0

As calorimetric combustion temperature is hardly attainable due to thermal energy consumption for partial dissociation of combustion products, theoretical temperature is calculated with account of partial dissociation of carbon dioxide and water vapour [6, 9]. Dissociation process can be described with the following thermochemical equations:

$$CO_2 \leftrightarrow CO + 0.5O_2 - 3{,}045\ \text{kkal/m}^3;$$

$$H_2O \leftrightarrow H_2 + 0.5O_2 - 2{,}580\ \text{kkal/m}^3.$$

A fast but approximate method to determine theoretical combustion temperature is the use of graphical dependence of the dissociation rate on the temperature and partial pressure of components [6, 9, 13].

For accurate estimation of theoretical temperature it shall be remembered that the combustion products contain both CO_2 and H_2O, and five constituent components shall be balanced:

$$\begin{tikzcd}
CO_2 \arrow[dr, no head] & & CO \arrow[dl, no head] \\
 & O_2 \arrow[dl, no head] \arrow[dr, no head] & \\
H_2O & & H_2
\end{tikzcd}$$

Thus, there are three unknown variables - combustion temperature t_{theor}, dissociation rate $CO_2 - x$ and dissociation rate $H_2O - y$. These variables can be found with the following equations:

$$Q^{р}_{н} - Q_{diss} = t_{theor} \sum V_i c_i;$$

for reaction $2CO_2 \leftrightarrow 2CO + O_2$

$$\lg K_1 = f_1(t_{theor}); \tag{1}$$

for reaction $2H_2O \leftrightarrow 2H_2 + O_2$

$$\lg K_2 = f_2(t_{theor}). \tag{2}$$

The first equation shall be deducted from the second one and divided by 2:

for reaction $CO + H_2O \leftrightarrow H_2 + CO_2$

$$\lg K_3 = \frac{\lg K_2 - \lg K_1}{2} = f_3(t_{\text{theor}}) . \qquad (3)$$

The numeric values of equilibrium constants K_1 и K_2 shall be determined using Sackur formulas:

$$\lg K_1 = \frac{29{,}250}{T} - 2.5\lg T - 1.24 ;\ \lg K_2 = \frac{25{,}000}{T} - 2.5\lg T + 2.68 .$$

Sticking to the main principle of N.S.Kurnakov's schools: 'Theoretical problems shall be studied at facilities of high technical importance'[13, 17], the Mining Institute has developed an analytical calculation methods [7], different from earlier proposed methods by its higher accuracy, as it does not require the construction of graphs based on which it is hard to determine an accurate temperature value. We would like to illustrate a proposed method for calculation of theoretical combustion temperature on example of a generator gas.

Equilibrium constants for reactions (1) and (3) are equal to:

$$K_1 = \frac{(\mathrm{CO_2})^2}{(\mathrm{CO})^2\,\mathrm{O_2}} = \frac{(1-x)^2(1+0.079x+0.046y)}{x^2(0.079x+0.046y)} ;$$

$$K_3 = \frac{(\mathrm{CO})(\mathrm{H_2O})}{(\mathrm{CO_2})(\mathrm{H_2})} = \frac{x(1-y)}{(1-x)y} .$$

We used successive approximation method to solve a system of non-linear equations [3]. Let's build a system of equations with a convergence attribute, and to simplify the calculations, introduce a new value z :

$$\begin{cases} z = \dfrac{K_1x^2}{(1-x)^2} = \dfrac{(1+0.079x+0.046y)}{(0.079x+0.046y)} \rightarrow x = \dfrac{-z \pm \sqrt{K_1 z}}{(K_1 - z)} ; \\ y = \dfrac{x}{K_3(1-x)+x} . \end{cases}$$

Equilibrium temperature 1,600 °C, lg $K_1 = 1.568 \cdot 10^6$ and lg $K_3 = 6.69$.

Let's assume that $x = 0.02$.

Then

$$y = \frac{0.02}{6.69(1-0.02)+0.02} = 0.003 ;$$

$$z = \frac{1.568 \cdot 10^6 \cdot 0{,}02^2}{(1-0.02)^2} = 0.5831 \cdot 10^3 ;$$

$$x = \frac{-0.5831 \cdot 10^3 \pm \sqrt{1.568 \cdot 10^6 \cdot 0.5831 \cdot 10^3}}{(1.568 \cdot 10^6 - 0.5831 \cdot 10^3)} = 0.01892 .$$

Let's assume that $x = 0.01892 \rightarrow y = 0.0028713 \rightarrow z = 0.6158 \cdot 10^3$.

We use the same calculation pattern to get x, y and z values, until the received values match the set values. Calculation results are shown in Table 3 which also demonstrated changes in x and y values versus the initial value.

Table 3

Results of Calculations using Successive Approximation Method

Step	*x*	$\Delta x = x_n - x_{n+1}$	y	$\Delta y = y_n - y_{n+1}$	*z*
			Temperature 1,600 °C		
1	0.02000		0.0030000		$0.5831\cdot10^3$
2	0.01892	+0.00108	0.0028713	+0.0001287	$0.6158\cdot10^3$
3	0.01944	–0.00052	0.0029553	–0.0000840	$0.5992\cdot10^3$
4	0.01918	+0.00026	0.0029148	+0.0000405	$0.6074\cdot10^3$
5	0.01931	–0.00013	0.0029350	–0.0000202	$0.6033\cdot10^3$
6	0.01924	+0.00007	0.0029240	+0.0000110	$0.6054\cdot10^3$
7	0.01927	–0.00003	0.0029290	–0.0000050	$0.6045\cdot10^3$
			Temperature 1,633 °C		
1	0.02000		0.0030000		$0.5831\cdot10^3$
2	0.02619	–0.00619	0.0038305	–0.0008305	$0.4464\cdot10^3$
3	0.02299	+0.00320	0.0033501	+0.0004804	$0.5083\cdot10^3$
4	0.02450	–0.00221	0.0035758	–0.0002257	$0.4772\cdot10^3$
5	0.02376	+0.00174	0.0034641	+0.0001117	$0.4921\cdot10^3$
6	0.02411	–0.00035	0.0035186	–0.0000545	$0.4847\cdot10^3$
7	0.02394	+0.00017	0.0034915	+0.0000271	$0.4887\cdot10^3$
8	0.02403	–0.00009	0.0035065	–0.0000150	$0.4864\cdot10^3$
9	0.02398	+0.00005	0.0034975	+0.0000090	$0.4875\cdot10^3$
10	0.02400	–0.00002	0.0035020	–0.0000045	$0.4870\cdot10^3$
			Temperature 1,629 °C		
1	0.02400		0.0035000		$0.4871\cdot10^3$
2	0.02308	+0.00082	0.003381	+0.000119	$0.5062\cdot10^3$
3	0.02352	–0.00044	0.003449	–0.000068	$0.4967\cdot10^3$
4	0.02331	+0.00021	0.003416	+0.000033	$0.5014\cdot10^3$
5	0.02341	–0.00010	0.003432	–0.000016	$0.4992\cdot10^3$
6	0.02336	+0.00005	0.003425	+0.000007	$0.5001\cdot10^3$
7	0.02338	–0.00002	0.003428	–0.000003	$0.4996\cdot10^3$
8	0.02337	+0.00001	0.003426	+0.000002	$0.4999\cdot10^3$
9	0.02338	–0.00001	0.003426	–0.000000	

Composition (m^3) and number of combustion products (% of total volume):

CO_2	$0.1592(1 - 0.01927)$	0.1561	0.1558
CO	$0.1592\cdot0.01927$	0.0031	0.0031
H_2O	$0.0923(1 - 0.002929)$	0.0920	0.0918
H_2	$0.0923\cdot0.002929$	0.0003	0.0003
O_2	$0.079\cdot0.01927 + 0.046\cdot0.002929 + 0.0119$	0.0141	0.0136
N_2	0.7352	0.7352	0.7340
SO_2	0.0014	0.0014	0.0014
Total	$1 + 0.079\cdot0.01927 + 0.046\cdot0.002929$	1.0017	1

Calorific content of combustion products:

Generator gas combustion	2,728 / 1.0017 = 2,723 kJ/m^3
CO_2 Dissociation	–3,045·4.19·0.0031 = –39.6 kJ/m^3
H_2O Dissociation	–2,580·4.19·0.0003 = –3.2 kJ/m^3
Total	i_0 = 2,723 – 36.9 – 3.2 = 2,680 kJ/m^3

Temperature with that calorific content

$$t = \frac{i_0}{\sum V_i \bar{c}_i},$$

where i_0 is the calorific content of the combustion products, kJ/m^3; V_i is the volume fraction of the combustion product; $\bar{c}_i$ is the average thermal capacity of the combustion product, kJ/($m^3 \cdot$ K).

Let's substitute thermal capacity values at set temperature until the identical equation is received:

$$t_i = \frac{2,680}{0.1558\bar{c}_{CO_2} + 0.7340\bar{c}_{N_2} + 0.0136\bar{c}_{O_2} + 0.0918\bar{c}_{H_2O} + 0.0031\bar{c}_{CO} + 0.0003\bar{c}_{H_2} + 0.0014\bar{c}_{SO_2}}.$$

Let's assume that

$$t_i = 1,600\ °C \xrightarrow{\text{Step 1}} 1,634\ °C \xrightarrow{\text{Step 2}} 1,632\ °C \xrightarrow{\text{Step 3}} 1,633\ °C.$$

Equilibrium temperature 1,633 °C, lg $K_1 = 0.8054 \cdot 10^6$ and lg $K_3 = 7.0$.
Let's assume that

$$x = 0.02 \rightarrow y = 0.003 \rightarrow z = 0.5831 \cdot 10^3.$$

Composition (m^3) and number of combustion products (% of total volume):

CO_2	0.1592(1-0.02400)	0.1554	0.1558
CO	0.1592·0.02400	0.0038	0.0038
H_2O	0.0923(1-0.003502)	0.0920	0.0918
H_2	0.0923·0.003502	0.0003	0.0003
O_2	0.079·0.02400+0.046·0.003502+0.0119	0.01400	0.0140
N_2	0.7352	0.7352	0.7336
SO_2	0.0014	0.0014	0.0014
Total	1+0.079·0.02400+0.046·0.003502	1.0021	1

Calorific content of combustion products:

Generator gas combustion	2,728 / 1.0021 = 2,722 kJ/m^3
CO_2 Dissociation	–3,045·4.19·0.0038 = –48.5 kJ/m^3
H_2O Dissociation	–2,580·4.19·0.0003 = –3.2 kJ/m^3
Total	i_0 = 2,722 – 48.5 – 3.2 = 2,676 kJ/m^3

Temperature with account of determined calorific content:

$$t_i = \frac{2,676}{0.1558\bar{c}_{CO_2} + 0.7336\bar{c}_{N_2} + 0.014\bar{c}_{O_2} + 0.0918\bar{c}_{H_2O} + 0.0038\bar{c}_{CO} + 0.0003\bar{c}_{H_2} + 0.0014\bar{c}_{SO_2}}.$$

Let's assume that

$$t_i = 1,600\ °C \xrightarrow{\text{Step 1}} 1,632\ °C \xrightarrow{\text{Step 2}} 1,629\ °C \xrightarrow{\text{Step 3}} 1,629\ °C.$$

Equilibrium temperature 1,629 °C, lg $K_1 = 0.872 \cdot 10^6$ and lg $K_3 = 6.963$.
Let's assume that

$$x = 0.024 \rightarrow y = 0.0035 \rightarrow z = 0.4871 \cdot 10^3.$$

Composition (m^3) and number of combustion products (% of total volume):

CO_2	0.1592(1 – 0.02338)	0.1554	0.1552
CO	0.1592·0.02338	0.0037	0.0037
H_2O	0.0923(1 – 0.003426)	0.0919	0.0918
H_2	0.0923·0.003426	0.0003	0.0003
O_2	0.079·0.02338 + 0.046·0.003426 + 0.0119	0.0139	0.0139
N_2	0.7352	0.7352	0.7337
SO_2	0.0014	0.0014	0.0014
Total	1 + 0.079·0.02338 + 0.046·0.003426	1.002	1

Calorific content of combustion products:

Generator gas combustion	2,728 / 1.0020 = 2,722 kJ/m^3
CO_2 Dissociation	– 3,045·4.19·0.0037 = –47.2 kJ/m^3
H_2O Dissociation	– 2,580·4.19·0.0003 = –3.2 kJ/m^3
Total	i_0 = 2,722 – 47.2 – 3.2 = 2,672 kJ/m^3

Temperature with account of determined calorific content:

$$t_i = \frac{2,672}{0.1552\bar{c}_{CO_2} + 0.7337\bar{c}_{N_2} + 0.0139\bar{c}_{O_2} + 0.0918\bar{c}_{H_2O} + 0.0037\bar{c}_{CO} + 0.0003\bar{c}_{H_2} + 0.0014\bar{c}_{SO_2}}.$$

Let's assume that

$$t_i = 1,629\ ^\circ\mathrm{C} \xrightarrow{\text{Step 1}} 1,627\ ^\circ\mathrm{C} \xrightarrow{\text{Step 2}} 1,627\ ^\circ\mathrm{C}.$$

The assumed temperature 1,629 °C and the determined temperature 1,627 °C are different by 2 °C, which is quite sufficient for thermal calculation. Thus, the accuracy of calculations depend on the number of calculation steps.

Conclusions

1. With account of technological peculiarities, location and infrastructure of Achinsk refinery, it shall be noted that the proposed use of brown coals of Kansk-Achinsk Basin as a sintering fuel is specific to RUSAL Achinsk OJSC.

2. Acceptable calorific value $Q_{\text{н}}^{\text{р}} = 5{,}870$ kJ/m^3 and theoretical combustion temperature of over 1,600 °C of generator gas at the existing pyrometric rate for tubular furnaces make it a possible fuel for sintering kilns and alumina calciners which can replace black oil and natural gas, access to which is restricted for some of the regions.

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Authors: **O.A.Dubovikov,** *Dr. of Engineering Sciences*, *Professor*, *dubovikov_oa@mail.ru* (*Saint-Petersburg Mining University, Russia*), **V.N.Brichkin,** *Dr. of Engineering Sciences*, *Head of Department*, *brichkin52@mail.ru* (*Saint-Petersburg Mining University, Russia*).

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