Mathematical modeling of energy consumption in the production of hydrogen

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Abstract. The article discusses the technological process of hydrogen production at metallurgy. Mathematical models of the dependence of power consumption and specific consumption depending on various parameters have been obtained, which make it possible to calculate and predict. In the electrolyzer, the change in the component of the specific power consumption by the amount of potassium dichromate (chromium peak) over time is analyzed. Therefore, the analysis of the dependence of the specific power consumption in time was carried out directly on the basis of the results of an experimental study of the dependence of the change in time of the voltage on the electrolyzer when the electrolyzer was loaded with chromium peak. The most important issue of reducing electricity consumption due to the use of a gas holder in the mode of consumer-regulator has been investigated. Controlling the level of deviations in power consumption (±2%) in comparison with the normative (±5%) allows increasing the margin of "safety" in terms of load regulation time, reducing the likelihood of it going beyond the normative level and, accordingly, reducing the payment for deviations in the volume of electrical energy consumption.

1. Introduction

In the energy shop of the non-ferrous metallurgy enterprise under consideration, hydrogen is produced, which is necessary to meet the needs of the shops in process gas, which is the main reducing agent in furnaces and welding machines. The structural technological scheme of hydrogen production is shown in Figure 1 [1-4].

The decomposition of distilled water into hydrogen into oxygen (1) is carried out in electrolyzers of the FV-500 M type. The hydrogen and oxygen obtained as a result of the decomposition of water are washed from alkali (2) in bubblers. Oxygen purified from alkali is sent to an oxygen-filling station for compression. Hydrogen partially enters the gas holder, and the main part of the hydrogen passes through water-ring gas blowers of the VK-50 type or compressors of the 202 GP 20/2 type to maintain the required hydrogen pressure (3). After gas blowers or compressors, hydrogen is purified and dried from moisture and oxygen (4) (hydrogen content in hydrogen-gas by volume is not less than 99.983%) in the installation, the most energy-intensive consumers, which are calcining furnaces.
completing operations (1–4), hydrogen is directed to the distribution manifold, from where it is transported through pipelines (5) to the shops to the consumers [5-7].

Figure 1. Structural flow diagram of hydrogen production.

All shop consumers belong to the II (electrolyzers, calcining furnaces, gas blowers, compressors) and III (electric distillers) categories of power supply reliability. Table 1 shows the energy characteristics of the main consumers of electricity in the power shop.

**Table 1.** Energy characteristics of the main consumers of electricity in the power shop.

| №  | Receiver name and power characteristics | Electrolyzer | Gas blower | Calcining furnace | Compressor |
|----|----------------------------------------|--------------|------------|------------------|------------|
| 1  | Consumer type                          | FV-500 M     | VK-50      | -                | 202 GP 20/2|
| 2  | Power, kWt                             | 2993         | 200        | 200              | 105        | 55        |
| 3  | Temperature, °C                        | 60-80        | 40         | 420-470          | 420-470    | 60        |
| 4  | Performance, m³/hour                   | 536          | 3000       | 1500             | 750        | 1200      |

2. Materials and methods

Methods of mathematical statistics, factorial and regression analysis are used for the experimental study of the power consumption of consumers of the power plant [19-22]. The measurements were carried out during the implementation of an energy survey of a non-ferrous metallurgy enterprise using modern measuring systems [8–11, 24].

Based on the results of experimental studies, representative samples of active power \( P \), energy consumption \( W \) and hydrogen production \( V \) were formed, statistical estimates were obtained for the parameters under study, and graphs of the dependence \( P = f(t) \), \( V = f(t) \) and \( W = f(t) \) presented in Figure 2.

In the course of analyzing the dependencies shown in Figure 2, a mathematical model was built in the form of a regression equation for the dependence of energy consumption \( W \) on hydrogen production \( V \), which has the form: \( W = 4.6844V - 339.74 \). The coefficient of accuracy of the approximation is: \( R^2 = 0.9974 \).
3. Change in the component of specific electricity consumption by the amount of potassium dichromate (chromium peak) over time

Due to the complex and implicitly expressed process of electrolysis, a direct assessment of the effect of the amount of potassium dichromate (chromium peak) in the electrolyzer on the specific power consumption is impossible [23].

Therefore, the analysis of the dependence $W_{\text{specific}} = f(T)$ was carried out directly on the basis of the results of an experimental study of the dependence of the change in time of the voltage on the electrolyzer when the electrolyzer is loaded with chromium peak.

In accordance with the flow chart, 70 kg of chromium pick was loaded into the FV-500M electrolyzer. Over the next 12 days, the values of voltage, current in the electrolyzer, and hydrogen production were recorded in online mode.

The value of the electrolysis current $I$ during the entire time of the experiment remained constant, equal to $I = 5.6 \text{kA}$. The graph of dependences $U = f(T)$, $W = f(T)$, $V = f(T)$ is shown in Figure 3.
From the graph (Figure 3), it follows that in the process of dissolution of the chromic peak, the voltage on the electrolyzer required for the normal course of the hydrogen generation process decreases from 385 to 380 V. At the same time, the total and specific power consumption decreases from 4.07 kWh/m³ to 2.91 kWh/m³.

Based on the data in Figure 3, the regression equations of the dependencies were constructed using the least squares method $U = f(T)$, $W = f(T)$, $V = f(T)$:

\begin{align}
U(T) &= 386.39 - 0.5455 T, \\
W(T) &= 1.9T^5 - 54.7T^4 + 549.8T^3 + 2498.7T^2 + 6181.7T + 25176, \\
V(T) &= 2.88T^4 - 67.9T^3 + 489.8T^2 + 859.1T + 7746.6.
\end{align}

Correlation coefficients: $r_{U,T} = -0.995; r_{W,T} = -0.08; r_{V,T} = 0.85$. Coefficients of determination: $R^2 = 0.99; R^2 = 0.88; R^2 = 0.9$. Dependences of energy consumption $W = f(U)$ and specific power consumption $W_{\text{specific}} = f(U)$ are shown in Figure 4.

\[ W_{\text{specific}} = 0.104U - 35.9, \text{kWh/m}^3, \quad (4) \]

where $r_{\text{specific},U} = 0.889; R^2 = 0.9866$.

Complete dissolution of the chromic peak (zone 2) leads to a significant decrease in the specific power consumption at a voltage on the electrolyzer $U < 381$ V.

Regression equation within zone 2:

\[ W_{\text{specific}} = 266.07\ln(U) - 1577.7, \text{kWh/m}^3, \quad (5) \]

where $R^2 = 0.8122$.

Specific power consumption when using chrompeak is reduced by 1.4 times and energy saving for 1 hour is: $\Delta W = 1.2V, \text{kWh}$.

Due to a significant reduction in the specific and total power consumption, it is recommended to periodically add chromopic to the electrolyzer when the actual value of the specific power consumption is: $U = 381$ V.
consumption exceeds the calculated one, and the voltage on the electrolyzer $U > 381$ V. Calculations show that the optimal addition of 35 kg of chromic peak every six months.

4. **Reduction of electricity consumption due to the use of a gas tank in the mode of consumer-regulator**

To create a supply of hydrogen and smooth out sudden pressure drops due to uneven consumption of it by the shops, the enterprise has a gas tank with a nominal capacity of 3000 m$^3$. Working capacity (from “minimum” to “maximum”) is 2400 m$^3$. In accordance with the requirements of the technological process, the volume of filling the gasholder with hydrogen is 800–1500 m$^3$.

The gas holder is the most efficient indirect consumer-regulator of electricity. Determining the current load on the shops in the on-line mode, it is possible to vary the hydrogen production by the electrolyzer within an hour, decreasing it during the peak hours of the day (the missing amount of hydrogen for technological purposes is taken from the gas holder), and increasing during the lowest load hours (excess of produced hydrogen discharged into the gas tank).

So, for example, from the graphs of electricity consumption ($W$) and payment for electrical energy, shown in Figure 5, it can be seen that in the period from 16-20 hours there is a load failure, due to which the payment for electricity increases, due to the payment for reducing electricity consumption declared by the enterprise.

![Figure 5](image_url)

**Figure 5.** Energy consumption and payment schedule.

Therefore, during this period, it is possible to increase the production of hydrogen entering the gas tank up to 200 m$^3$. Figure 4 shows the shaded time regions where, within $\pm 2\%$ of the standard level of deviations in power consumption, it is recommended to reduce the hydrogen production by 100 m$^3$ during the period from 9–15 hours and increase to 650 m$^3$ during the rest of the day. Controlling the level of deviations in power consumption ($\pm 2\%$) in comparison with the normative ($\pm 5\%$) allows increasing the margin of “safety” in terms of load regulation time, reducing the likelihood of it going beyond the normative level and, accordingly, reducing the payment for deviations in the volume of electrical energy consumption.
The results obtained in the course of experimental studies were used in works [12–18].

5. Conclusion

In the electrolyzer, the change in the component of the specific power consumption by the amount of potassium dichromate (chromium peak) over time is analyzed. Due to the complex and implicitly expressed electrolysis process, a direct assessment of the effect of the amount of potassium dichromate (chromium peak) in the electrolyzer on the specific power consumption is impossible. Therefore, the analysis of the dependence of the specific power consumption in time was carried out directly on the basis of the results of an experimental study of the dependence of the change in time of the voltage on the electrolyzer when the electrolyzer was loaded with chromium peak. Due to a significant reduction in the specific and total power consumption, it is recommended to periodically add chromopic to the electrolyzer when the actual value of the specific power consumption exceeds the calculated one, and the voltage on the electrolyzer \( U > 381 \) V. Calculations show that the optimal addition of 35 kg of chromic peak every six months.

The most important issue of reducing electricity consumption due to the use of a gas holder in the mode of consumer-regulator has been investigated. Controlling the level of deviations in power consumption (±2%) in comparison with the normative (±5%) allows increasing the margin of “safety” in terms of load regulation time, reducing the likelihood of it going beyond the normative level and, accordingly, reducing the payment for deviations in the volume of electrical energy consumption.

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