Power -cost effectiveness of hydrogen generation using gas wastes from steel smelting

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Abstract. Using the secondary energy resources will help us to reduce the specific natural gas consumption for hydrogen production. One of the most not used secondary energy resources in Russia is converter production of steel. In this production converted gas doesn’t used at all. Even more it’s burned on a flame that creates greenhouse gas (GNG) emission into the Earth atmosphere. The method of using converted gases for hydrogen production that we will look through below can help us to reduce the specific natural gas consumption with high economical efficiency. This method is based on thermochemical recuperation.

1. Introduction
Hydrogen production from natural gas is the most common and takes for about 85 % of total production [1]. Hydrogen from natural gas is commonly used in chemical and oil refining industry for production of technological products. The use of hydrogen, derived from organic fuels, is practically the same from the ecology point of view as the direct fuels use, since the harmful emissions in both cases are the same [1]. In one case greenhouse emissions to the atmosphere occur at the fuel stage and in the other the same emissions occur at the hydrogen production stage. Authors of [1] indicate that the production of hydrogen from organic fuels can be promising in capturing associated emissions to the atmosphere, including CO₂. There are perspectives of using the CO₂ when it is buried in old oil fields to increase oil production or in layers of iron-magnesium minerals to form carbonates [2].

Specific consumption of natural gas for hydrogen production by conversion methods is 0.43 – 0.66 (m³ nat. gas)/(H₂ m³) [3, 4] at a cost of 1.1 – 1.6 USD/kg [5] or 0.10 – 0.15 USD/(m³ H₂).

In order to increase the efficiency of hydrogen production from organic fuel, the task is to reduce the specific consumption of natural gas by using gas wastes, which will reduce the yield of greenhouse gases, as well as increase economic efficiency.

2. Thermochemical recuperation of high-temperature gas wastes
High-temperature gas wastes of industrial plants are secondary energy resources, which can be used in a complex way to obtain a new energy source. That source is synthesis gas. It’s possible by conversion of natural gas or other hydrocarbon-containing substance [6]. Synthesis gas can be used as a secondary fuel for power plants or as a raw material for processes, including hydrogen production. The complexity of recycling is that the conversion process uses both the heat of the gas waste and (partially or completely) the material stream of the gas waste.
In the case of thermochemical recuperation (TCR), a significant proportion of heat flow and up to 30% of the material flow of high-temperature gas wastes are recovered [6–9]. The oxidants during the conversion of natural gas or other hydrocarbon-containing substance are steam, exhaust gases (combustion products), as well as a mixture of steam and combustion products. Positive influence of TCR on characteristics of steam-gas plants and gas turbine plants was detected and investigated [11–14].

Production of converter steel in Russia is characterized by annual production of about 60 million tons, at the same time the potential of use of converter gases energy is 1250 thousand tons of conditional fuel and potential of reduction of emissions of carbon dioxide – 2140 thousand tons [15]. Authors of [16] present methods for utilization of converter gases by TCR methods for power generation [17], as well as by energy chemical accumulation (ECHA) method for hydrogen production [4, 18]. At the Russian metallurgical enterprises of the full cycle, the installation of gasolders for the utilization of converter gases is considered a promising direction [19, 20]. The development of systems of joint operation of gasgolder circuits with TCR elements in plants of Japan, Germany, China [22–24] is under way.

The earliest known works on utilization of converter gases based on ECHA are studies carried out since 1985 at the Department of Energy of High Temperature Technology of NRU "MPEI" under the direction of Professor A.D. Kluchnikov and presented in [25]. This scientific direction has been further developed in the works [26, 27]. Research on the utilization of converter gases for the production of hydrogen is devoted to work [4, 7, 16, 18, 27]. This paper focuses on results of the study of thermochemical energy recovery scheme of converter gases for hydrogen production based on natural gas conversion.

3. Characteristics of thermochemical recovery scheme of converter gases for hydrogen production

Converter gases can be used as a source of energy for the steam conversion of natural gas to produce hydrogen. The thermal scheme of this embodiment is shown in Figure 1.

![Figure 1. Thermal diagram of use of converter gas for steam conversion of natural gas with subsequent production of hydrogen: CGAC – Converter gas afterburning chamber; CR – conversion reactor; HSGM – heater of steam-gas mix; E – evaporator; HSI – hydrogen separation installation; CG – converter gas; GWO1, GWO2, GWO3, GWO4 – Gas wastes at outlet CGAC, CR, HSGM & E respectively; A – air supplied to converter gas afterburning chamber; SGM – steam-gas mix (mix of water vapor and natural gas) on an entrance and an exit HSGM; FW – feedwater; NG – natural gas; SNG – synthesis gas.](image-url)
percentage composition of converter gas [7]: N₂ = 14.62; CO₂ = 23.52; O₂ = 4.22; CO = 57.35; H₂ = 0.29;
percentage composition of natural gas: CH₄ = 89.7; C₂H₆ = 5.2; C₃H₈ = 1.7; C₄H₁₀ = 0.4; C₅H₁₂ = 0.1; CO₂ = 0.1; N₂ = 2.7;
synthesis gas temperature is 800 °C;
temperature of heated steam-gas mixture (SGM₂ flow) is 400 °C.

It is assumed that the synthesis gas at the outlet of the conversion reactor is in thermodynamic equilibrium. All inlet material flows have ambient temperature.

Results of the research are presented in Figure 2, 3 in the form of dependences of a specific rate V₅₂ (m³ hydrogen)/(m³ converter gas) and flue gas temperatures (GWO₄ stream in Figure 1) tₕ °C from a specific rate of natural gas VNG (m³ NG)/(m³ converter gas) at different specific flow rates of water vapour for the process of conversion Vsteam (m³ steam)/(m³ NG). Here and below, the volumes of natural gas and other gases are measured with conventional standard conditions 273.15 K and 101325 Pa. These results were obtained at a synthesis gas pressure Psg = 10 atm (0.98 MPa).

While VNG increase, the most part of the heat of the converter gas combustion products is consumed for steam conversion, whereby flue gas temperature decreases (Figure 3). If tₕ is reduced to the level of 115 – 120 °C, further increase of VNG is impractical. This explains the variation range of VNG shown in Figure 2, 3. Calculated studies lead to the conclusion that the change in Psg significantly affects the mode parameters of the plant.

It is interesting to estimate the level of b – natural gas specific consumption for hydrogen production (m³ natural gas)/(m³ H₂). It is obvious that b = VNG / V₅₂. The results of the evaluation are shown in Figure 4. The data of Figure 4 show natural gas specific consumption for hydrogen production can be 0.285 (m³ natural gas)/(m³ H₂) at synthesis gas pressure of 1 atm and 0.335 (m³ natural gas)/(m³ H₂) at synthesis gas pressure of 10 atm, which is lower than the characteristics of hydrogen production technologies used by 22–56 %.
4. Economic efficiency of hydrogen production based on thermochemical recuperation of converter gases

The analysis of the economic characteristics of the hydrogen production process according to the scheme shown in Figure 1 is carried out according to the procedures [28,29] with the following initial data.

1. Annual steel production – 11 million tons with operation of three converters with capacity of 400 tons in the mode "two converters in operation, one – in reserve". Specific output of gases wastes (converter gases) per unit of produced steel is $V_{CG} = 87.5 \frac{\text{m}^3}{\text{ton}}$.

2. The specific characteristics of hydrogen production are as follows:
   - synthesis gas pressure $p_{sg} = 10$ atm;
   - specific yield of hydrogen per unit of converter gas $V_{H2} = 0.896 \frac{\text{m}^3 \text{H}_2}{\text{m}^3 \text{converter gas}}$;
   - natural gas specific consumption for hydrogen production $b = 0.335 \frac{\text{m}^3 \text{natural gas}}{\text{m}^3 \text{H}_2}$;
   - specific steam consumption per conversion $V_{steam} = 3 \frac{\text{m}^3 \text{steam}}{\text{m}^3 \text{natural gas}}$;
   - specific electric power consumption for hydrogen production $e_{ep} = 0.038 \frac{\text{kWh}}{\text{m}^3 \text{H}_2}$ [3].

On the basis of these characteristics the amount of the produced hydrogen will be $G_{H2} = 862.4$ million $\text{m}^3/\text{year}$ or $g_{H2} = 99.8$ thousand $\text{m}^3/\text{hr}$, under a working condition 360 days a year.

Annual expenses of energy resources on hydrogen production will be:

- natural gas $B_{NG} = 288.75$ million $\text{m}^3/\text{year}$;
- water $G_{H2O} = 0.696$ million tons/year;
- electric power $P_{EP} = 32.771$ million kWh/year.

The following costs of natural gas, water and electricity are accepted for calculating energy and resource costs:

- cost of natural gas $R_{NG} = 5$ rub./$\text{m}^3$;
- cost of water $R_{H2O} = 40$ rub./ton; $R_{EP} = 5$ rub./kWh respectively.

To estimate capital costs, the project accepts the following data: unit costs for hydrogen production – 0.9 million dollars/(thousand $\text{m}^3$/hr) [2]; cost of gasgolder – 80 million rubles [15]; ruble exchange rate to dollar – 73 RUB/USD.

Based on it total capital expenditures are $K = 6637.5$ million rubles.

Term of implementation of the project is accepted as 2 years, while investments in the 1st year are 37%, and in the 2nd year – 63 %. The structure of capital expenditures for two years is shown in Table 1.

To estimate the annual cost of hydrogen production, the following costs are determined: energy and raw materials (natural gas, water, electricity); for repair and maintenance of an equipment; to the salary fund (SF); on amortization; on real estate charge. The results of economic criteria calculation are given in Table 2.

\[ TC_1 = B_{NG} \cdot R_{NG} + G_{H2O} \cdot R_{H2O} + P_{EP} \cdot R_{EP} = 1635 \text{ million rub / year}. \]  
\[ TC_2 = C_{ep} \cdot d_f = 3982.5 \cdot 0.1 = 398 \text{ million rub / year}, \]

where $C_{ep}$ is the cost of the equipment (see Table 1, Equipment procurement); $d_f = 0.1$ – the repair fees from the initial cost of the equipment.
| Name of a stage                  | 1st year | 2nd year | TOTAL by years: |
|---------------------------------|----------|----------|-----------------|
| Project works                   | 265.6    | 66.3     | 331.9           |
| Preparation of the territory    | 0.0      | 663.8    | 663.8           |
| Equipment procurement           | 1991.2   | 1991.3   | 3982.5          |
| Installation and construction works | 199.1   | 796.4    | 995.5           |
| Balancing and commissioning     | 0.0      | 663.8    | 663.8           |
| TOTAL on stages                 | 2455.9   | 4181.6   | 6637.5          |

Table 1. Structure of capital expenditures, million rubles.

In the calculation of $TC_3$ costs for salary fund (SF) it is accepted: additional number of employees for hydrogen production sites – 16 people; average monthly salary – 80 thousand rubles; contributions to social funds – 30.2 %.

As a result, $TC_3 = 20$ million rubles/year.

Equipment amortization costs $TC_4$

$$TC_4 = \frac{C_{ce}}{n_e} = \frac{6637.5}{20} = 331.87 \text{ million rub / year},$$  \hspace{1cm} (3)

where $C_{ce}$ – the cost of capital expenditure (see tab. 1 in the line "Total"); $n_e = 20$ years – service life of the equipment.

$TC_5$ real estate charge for the first year

$$TC_5 = \frac{T_{base} \cdot T_{rate}}{100} = \frac{6637.5 \cdot 2.2}{100} = 146 \text{ million rub / year},$$  \hspace{1cm} (4)

where $T_{base} = 6637.5$ million rubles – tax base for real estate charge calculation for the first year of operation; $T_{rate} = 2.2 \%$ – tax rate.

Table 2. Calculation of economic criteria for the project at the sale of hydrogen at the cost of 20 rubles/m$^3$.

| Period, year | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Cash flow, million rub/year | 0     | 0     | 16317 | 33213 | 50709 | 68826 | 87587 | 107015| 127132| 147963|
| Risk discounting ratio      | 0.1566| 0.0566| 0.0566| 0.0566| 0.0566| 0.0566| 0.0566| 0.0566| 0.0566| 0.0566|
| Discount cash flow, million rub/year | 0 | 0 | 10547 | 26651 | 38512 | 49473 | 59587 | 68906 | 77476 | 85343 |
| Investment with inflation, million rub/year | 2542 | 7110 | 7883 | 9046 | 10744 | 13207 | 16803 | 22127 | 30157 | 42539 |
| Net present value NPV, million rub/year | -2542 | -7110 | 2663 | 17605 | 27768 | 36265 | 42784 | 46779 | 47320 | 42805 |
| Profitability index $PI$    | 0.0   | 0.0   | 1.3   | 2.9   | 3.6   | 3.7   | 3.5   | 3.1   | 2.6   | 2.0   |
| Internal rate of return $IRR$ | 0.0%  | 0.0%  | 1.3%  | 2.9%  | 3.6%  | 3.7%  | 3.5%  | 3.1%  | 2.6%  | 2.0%  | 108 %  |
Total costs for the first year of operation

\[ TC = TC_1 + TC_2 + TC_3 + TC_4 + TC_5 = 2531 \text{ million rub/year}. \]  

(5)

Production cost 1 m\(^3\) H\(_2\) for the first year of operation

\[ PC = \frac{TC}{G_{H_2}} = \frac{2531}{862.4} = 2.93 \text{ rub/(m}^3\text{ H}_2). \]  

(6)

Production cost is about 0.04 USD/(m\(^3\) H\(_2\)) or $0.41/kg, which is on average 3.3 times lower than in [5].

The assessment of the cost of selling hydrogen at the moment is quite a discussion point, as the hydrogen market in the world is not developed. For calculation of the revenues from hydrogen sale the cost \(C_{H_2}=20 \text{ rub/m}^3\) is accepted, this value is close to the cost of energy equivalent amount of gasoline in the Russian market. Annual revenue from hydrogen sales will be:

\[ TR = G_{H_2} \cdot C_{H_2} = 862.4 \cdot 20 = 17248 \text{ million rub/year}. \]  

(7)

In order to assess the economic efficiency of hydrogen production in TCR of converter gases, it is proposed to define a number of criteria.

Net present value (NPV) is calculated by formula

\[ NPV = \sum_{i=1}^{t} \frac{CF_i}{(1+i)^t} - \sum_{i=1}^{t} \frac{Inv_i(1+i)^t}{100}, \]  

(9)

where \(CF_i\) – cash flow, rub; \(i\) – forecast annual average inflation rate, %; \(Inv_i\) – initial investment in the project, rub; \(t\) – number of years of project implementation; \(d\) – discount rate.

Benefit-cost ratio, profitability index – \(PI\)

\[ PI = \frac{\sum_{i=1}^{t} \frac{CF_i}{(1+i)^t}}{\sum_{i=1}^{t} \frac{Inv_i(1+i)^t}{100}}, \]  

(10)

Internal rate of return – IRR – is defined from equation

\[ 0 = \sum_{i=1}^{t} \frac{CF_i}{(1+IRR)^t} - \sum_{i=1}^{t} \frac{Inv_i(1+i)^t}{100}. \]  

(11)

Risk discounting factor

\[ d = d_i + P/100. \]  

(12)

Risk adjustment accepted 13% for production and promotion of new product or 5% for development of production on the basis of mastered technology; \(d_i\) – discount rate:

\[ d_i = \frac{r-i}{100+i} = \frac{6.25-3.5}{100+3.5} = 0.02657, \]  

(13)

where \(r = 6.25\%\) – refinancing rate; \(i = 3.5\%\) – inflation rate. The risk discounting ratio is 0.1566 before return on investment and 0.0566 after return on investment.

From submitted NPV data Table 2 shows that the discounted payback period is 2.73 years and the project will pay off within 1 year of operation. On this basis, it can be concluded that the project has a sufficiently high economic efficiency. The results of the analysis show that the proposed technical solution is characterized by high economic indicators and risks related to the promotion of a new product – hydrogen – to the market. This is indicated by the high discount ratio, which leads to a decrease in the growth of NPV given the time, but after the payback period of the project.

**Conclusion**

The scheme of hydrogen production based on thermochemical recuperation of gas wastes of steel smelting production has been developed and investigated.
Research of the heat-technical characteristics of the scheme leads to the conclusion that its implementation will allow to organize the production of hydrogen with the specific consumption of natural gas by 22–56% lower than in the current technologies.

The analysis of the economic indicators of the scheme has found that in the case of converter steel production with a capacity of 11 million tons per year it is possible to obtain 862.4 million m$^3$ of hydrogen annually at a cost of 0.41 dollars/kg with a discounted payback period of 2.73 years from the beginning of the project.

The results of the study make it possible to conclude on the high energy-economic efficiency of the considered technical solution for hydrogen generation using gas wastes of steel smelting production.

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