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Energy Efficiency of Hydrogen Technologies on Thermal Power Plant

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ABSTRACT

The article is devoted to the current state of hydrogen economy and its prospects from the ecological and energy points of view. The article considers possibilities of applying hydrogen as efficient fuel for power boilers. The analysis of foreign experience in using hydrogen in power generation is considered. The calculations of impact of fuel composition on boilers' energy characteristics are presented. The article considers several current issues of hydrogen application for power generation. The technology of combining thermal power plant cycle with the steam methane reforming process for mutual efficiency enhancement is proposed.

Keywords: *Hydrogen economy, Energy efficiency, Boiler-plant.*

1. INTRODUCTION

Hydrogen economy is one of the most promising branches of energy industry, and global interest in hydrogen is steadily rising every year. In spite of the inevitability of energy transition from conventional to alternative energy sources, nowadays renewable power generation is not ready to provide for the whole market. That's why a lot of specialists consider some "transitional period" and hydrogen as its main fuel.

Hydrogen H_2 is a gas with the highest heating value – 140 MJ/kg (about 3 times greater than of natural gas). During hydrogen combustion only water vapour is formed, and because of zero CO_2 emission it's considered to be eco-friendly fuel. Hydrogen cannot be directly obtained in nature, but there are about 200 methods of hydrogen production, with organic fuel or water as feedstock. It's also possible to transport and store hydrogen for a long time both in liquid and gaseous state. Nowadays about a half of global hydrogen is produced from organic feedstock – coal or natural gas, and the most widespread technology is steam methane reforming.

Current rate of hydrogen production and consumption is about 70 million ton per year, and its' main consumers are chemical industry, metallurgy and oil processing. But according to prediction of some specialists, by 2050 the greatest demand in hydrogen will be set by energy industry – more than 370 million tons per year. Hydrogen share in global power production will amount to 7–24 %, according to the different authors [1].

There are several key advantages of hydrogen, which make it so attractive and perspective. First of all, hydrogen can be burned in present energy plants with considerable improvement of ecological situation. And it is also possible to use hydrogen as a very efficient energy storage unit, enable to integrate uneven electrical output from renewable energy sources into united power grid.

2. LITERATURE REVIEW

Many countries, especially whose with poor mineral resources, have high hopes for hydrogen economy's future. For example, according to "A hydrogen strategy for a climate-neutral Europe", about 12 and 18 million tons of hydrogen per year will be produced and consumed in European Union by 2030 and 2050 respectively. [2] In Japan similar document "Strategic Roadmap for Hydrogen and Fuel Cells" announces increase in hydrogen consumption up to 10 million annually by 2050. [3]

Besides fuel cells, the most promising area of hydrogen application is large power units – gas turbines and combined cycle power plants. Engineering researches in that sphere have been carrying out for more than 30 years, and their current state can be estimated from papers [4–7].

For instance [4], General Electric, prominent American gas turbine manufacturer, in 2020 had reported 75 gas turbine units operating on hydrogen-rich fuel mixture with total operating time more than 6 million hours and power output above 300 TWt. These numbers include 25 gas turbines working on fuels with more than 50 % hydrogen part by volume (total operating time – 1 million hours).

Another leading company – German conglomerate Siemens – is successfully working on next generation gas turbines, able to safely work on pure hydrogen. In 2019 the company presented several models, thoroughly described in article [5].

Analyzing other sources [6,7] one can get a full view of hydrogen advantages as a fuel – namely, increasing of thermal efficiency and reduction in CO_2 emission. However, there still are some drawbacks, including:

- low density of hydrogen, resulting in additional complication of fuel supply system
- High rate of flame propagation (special burners are needed for stable combustion)
- explosion hazard and high adiabatic flame temperature of hydrogen
- increasing NOx formation due to higher temperature in combustion chamber

In addition to hydrogen combustion difficulties mentioned above, there is another outstanding problem, connected with this fuel – issue of storage and transportation of hydrogen in the amount that energy industry will probably require. This problem is described in details in articles [8, 9]. Another challenge for widespread hydrogen utilization is the high cost of its production that is proved further in the article by Figure 8.

Nowadays the difficulties listed above basically can be solved, and current hydrogen projects demonstrate high energy efficiency. And speaking about CO_2 formation, accompanying steam methane conversion as the most widespread technology of hydrogen production, nowadays there are many technologies enable to capture, utilize and store this gas (CCUS) [10]. There are also prototypes of combining TPP and SMR cycles for simultaneous carbon dioxide capture with promised high efficiency. [11]

Still all the researches mostly relate to hydrogen combustion for gas turbines, not covering power boilers. For Russia, where the bulk of electricity output is produced by steam turbines, it's more of interest to estimate the possibilities of hydrogen utilization as a fuel for power boilers.

3. CALCULATION RESULTS

To estimate the efficiency of hydrogen applicability as a supplementary fuel for power boilers, the calculation of material and heat balance were performed. The power boiler "TTM-84 E-420-14-565" was chosen as an object of calculation. It is a drum-boiler with steam production capacity 420 t/h, steam outlet pressure 140 bar and steam outlet temperature 565 ^{0}C. Feed water temperature is 232 ^{0}C and inlet air temperature is 238 ^{0}C. The boiler can operate on both natural gas and fuel oil, in this paper only gas burning is considered.

For the calculation natural gas from Urengoy-Uzhgorod deposit was chosen, which composition by volume is shown in Table 1. The following calculations were carried out by increasing the volumetric and mass fraction of hydrogen in gas mixture, as shown in Tables 2,3. All calculations were made in accordance with [12].

Table 1. Initial gas composition

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2
Fraction by volume, %	98,9	0,12	0,01	0,01	0,9	0,06

Table 2. Gas composition calculated by volume

Component	H_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2
Fraction by volume, %	0	98,9	0,12	0,01	0,01	0,9	0,06
	10	94	0,11	0,01	0,009	0,81	0,05
	20	84,1	0,1	0,01	0,008	0,72	0,05
	30	69,2	0,08	0,01	0,007	0,63	0,04
	40	59,3	0,07	0,01	0,006	0,54	0,04
	50	49,5	0,06	0,01	0,005	0,45	0,03

Table 3. Gas composition calculated by mass

Component	H_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2
Fraction by mass, %	0	98	0,23	0,03	0,04	1,55	0,16
	10	88,2	0,2	0,03	0,034	1,4	0,15
	20	78,4	0,18	0,02	0,03	1,24	0,13
	30	68,6	0,16	0,02	0,026	1,09	0,12
	40	58,8	0,14	0,02	0,022	0,93	0,1
	50	49	0,11	0,01	0,019	0,78	0,08

The results of calculations are presented below on Figures 1–8 with design formulas and explanations.

3.1. Fuel composition effect on heating value

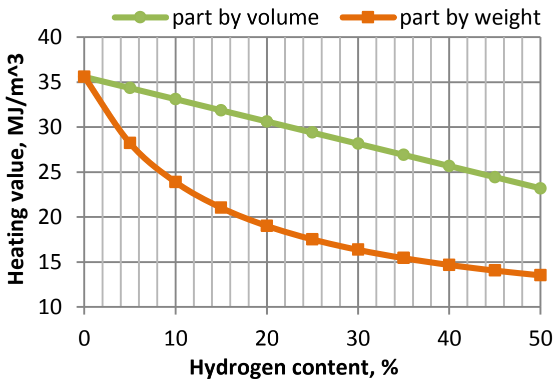

Figure 1 Volumetric heating value depending on gas composition.

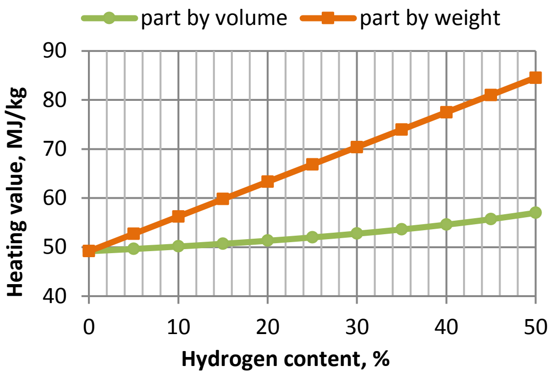

Figure 2 Mass heating value depending on gas composition.

Heating value is calculated by Equation:

$$Q = 0{,}01 * \left(Q_{H_2S} * H_2S + Q_{CO} * CO + \sum Q_{C_mH_n} * C_mH_n\right) \text{ kJ/m}^3 \quad (1)$$

where H_2S, CO, C_mH_n – parts by volume of corresponding gases in percent, $Q_{H_2S}, Q_{CO}, Q_{C_mH_n}$ – their volumetric heating values, kJ/m^3

As can be seen from the figures, with increasing hydrogen content the volumetric heating value of fuel mixture is decreasing, but mass heating value is increasing. It is caused by low density of hydrogen – only 0,09 kg/m^3 (0,7 kg/m^3 for natural gas). Therefore burning hydrogen-rich fuel may put a strain on fuel delivery system.

3.2. Fuel composition effect on its consumption with constant boiler loading

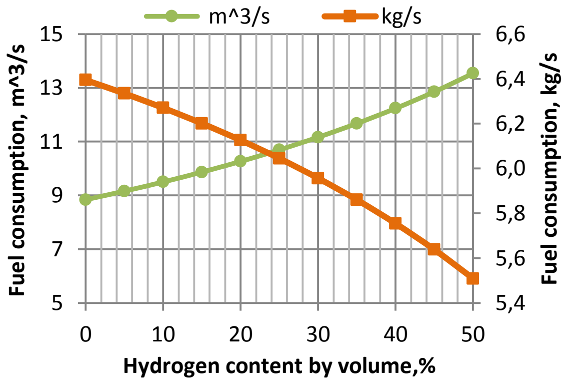

Figure 3 Fuel consumption depending on hydrogen content by volume

The rate of fuel consumption is calculated by Equation

$$B = {}^{Q * \eta}/_{D(h_{so} - h_{fw})}, \frac{\text{m}^3}{\text{s}} \left(\frac{\text{kg}}{\text{s}}\right) \quad (2)$$

where Q – heating value of fuel mixture, kJ/m^3 (kJ/kg), η –performance coefficient of boiler, D –steam capacity, kg/s, h_{so} и h_{fw} – enthalpy of outlet steam and feed water respectively, kJ/kg. Data for enthalpy's determination were placed in the boiler's description part above.

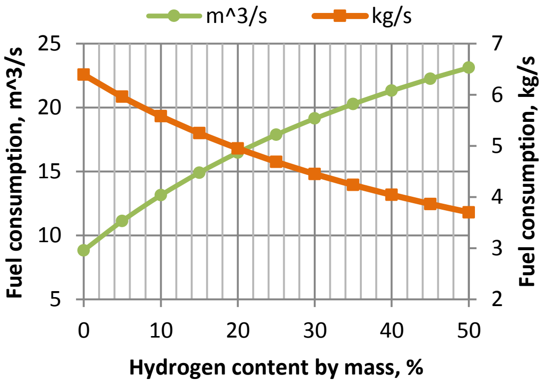

Figure 4 Fuel consumption depending on hydrogen content by mass

As can be seen from the figures, after increasing hydrogen content by volume up to 50 %, fuel consumption (kg/s) decreased by 1,2 times (1,7 times for 50 % hydrogen content by mass). Volumetric fuel consumption change was more dramatic, it increased by 1,5 and 2,5 times for 50 % hydrogen content by volume and mass respectively. The results obtained from Figures 3–4 reasonably correspond to whose from Figures 1–2.

3.3. Fuel composition effect on airflow rate and total amount of fuel-air mixture

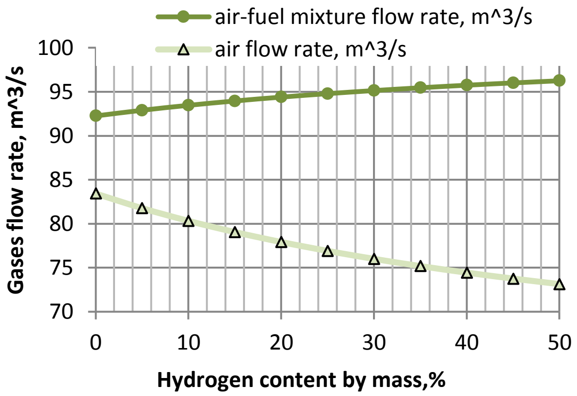

Figure 5 Air and air+fuel mixture flow rate depending on hydrogen content by mass

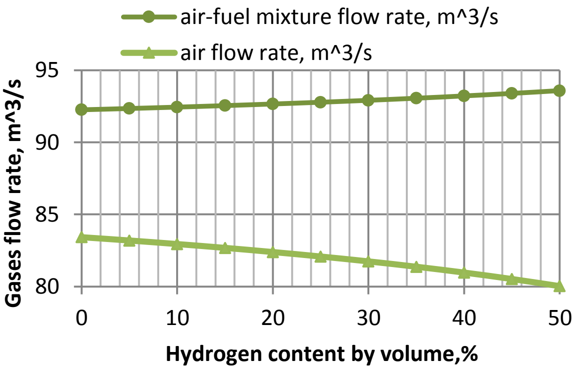

Figure 6 Air and air+fuel mixture flow rate depending on hydrogen content by volume

Stoichiometric air flow rate, required for combustion of a gas of specified composition is calculated by Equation:

$$V_0^H = 0{,}0476 * \left(0{,}5CO + 0{,}5H_2 + 1{,}5H_2S + \sum\left(m + \frac{n}{4}\right) C_mH_n - O_2\right), \frac{\mathrm{m}^3}{\mathrm{m}^3} \qquad (3)$$

where H_2S, CO, C_mH_n – parts by volume of corresponding gases in percents.

From presented material one can make a conclusion that for hydrogen-rich fuels less oxygen (so air) is required for stoichiometric combustion. But the total amount of fuel+air mixture delivered to burners for the same heat loading increases due to lower density of fuel.

3.4. Fuel composition effect on CO_2 emission

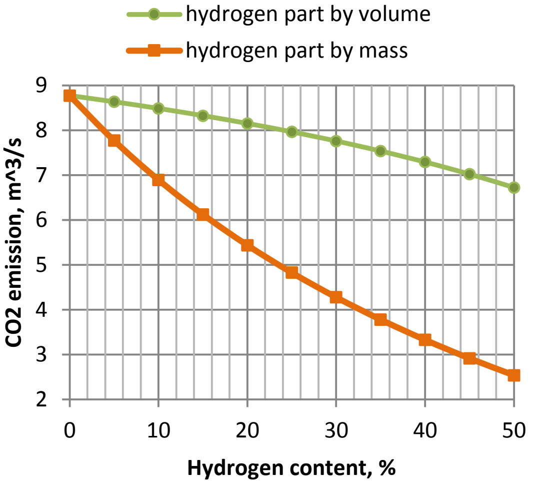

Figure 7 CO_2 formations depending on fuel composition.

The rate of CO_2 formation is calculated by Equation:

$$V_{RO_2}^H = 0{,}01(CO_2 + \mathrm{CO} + \sum mC_mH_n), \frac{\mathrm{m}^3}{\mathrm{s}} \qquad (4)$$

where CO_2, CO, C_mH_n – parts by volume of corresponding gases in percents

From the Figure 7 it can be seen that with increasing hydrogen content CO_2 emission considerably reduces (by 1,4 and 3,6 times for 50 % hydrogen content by volume and mass respectively). This opportunity of improving current ecological situation by using hydrogen is one of the main reasons of global interest in this fuel.

3.5. Fuel composition effect on energy cost

According to the up-dated sources [1], the cost of grey hydrogen (produced by steam methane reforming without CCUS) is about 7 rub/m^3, the cost of its feedstock (natural gas) – about 5,9 rub/m^3. The calculation of the cost of fuel mixture with different hydrogen content is presented on Figure 8.

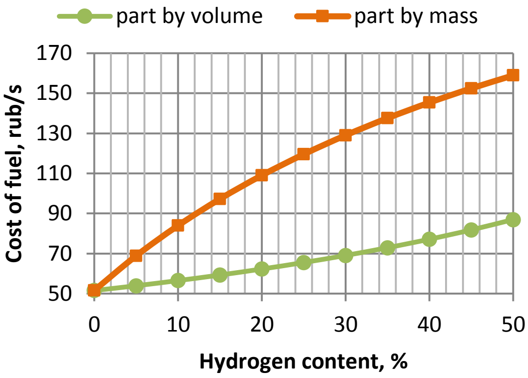

Figure 8 Fuel price depending on its composition.

As can be seen from the figure, additional hydrogen in the fuel mixture significantly increases fuel cost and the cost of produced thermal energy. The same relations were derived for hydrogen gas turbine stations. For example, the price of electricity from hydrogen power plant in Fusina, Enel was 5 times greater than from adjacent unit with pulverized fuel fired boiler [6].

4. CONCLUSIONS

Provided in this article calculations of main energy characteristics of power boiler E-420-14-565 are shown in Tables 1–2 and Figures 1–8. Analysing the data, the following conclusions can be made:

- with increasing hydrogen content in the fuel its volumetric heating value is decreasing, but heating value by mass is increasing.

This relation deserves particular attention, since in common practice all calculations for power boilers are performed for 1 m^3 of gaseous fuel.

- with increasing hydrogen content in the fuel the amount of air demanded for stoichiometric combustion significantly decreases. Due to this, the total amount of fuel+air mixture in furnace raises only slightly and partly compensated the necessity of passing higher amount of fuel through the delivery system.
- combustion of hydrogen-rich fuel considerably decreases the formation of carbon dioxide and consequently improves the environmental condition
- additional hydrogen in the fuel mixture increases the cost of produced energy, at least for current level of prices and technologies.

5. RESEARCH PROSPECTS

Considering the current ecological issues, in the near future global interest in hydrogen will steadily rise. But with regard to the mentioned above problems of hydrogen storage and transportation, its production directly on the place of consumption – on thermal power plants – seems promising.

The most suitable technology for that purpose can be steam methane reforming. In the Figure 9 the simplified layout of possible combination of thermal power plant and steam methane reformer cycles is presented.

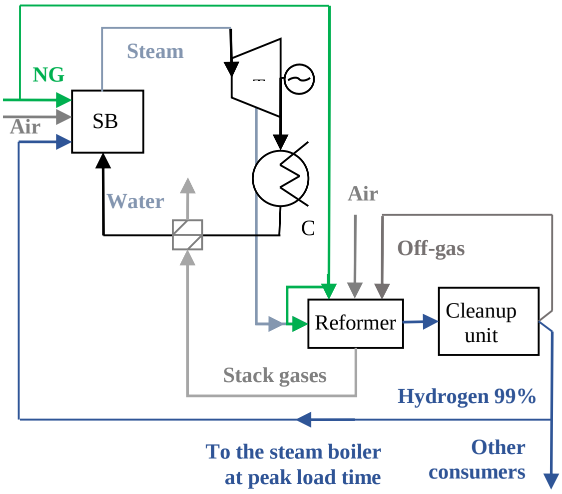

Figure 9 Possible scheme of combining electricity and hydrogen production on thermal power plant.

Steam methane conversion implies blending natural gas and high-temperature steam in a tube-type furnace with external heat input on the surface of aluminium – nickel catalyst. Besides the highest efficiency, this method is optimal for thermal power plants in particular, because both kinds of feedstock are present.

Combining electricity and hydrogen production can also increase the installed capacity utilization factor of power plant. During off-peak load periods at night extra steam can be used for hydrogen production in reformers; during peak load time this hydrogen can be burned in the boiler as an admixture for natural gas for higher power output.

Thus, hydrogen production on thermal power plants and its combustion as additional fuel during peak load can stand as complex solution for increasing efficiency of energy units with minimal negative impact on the environment.

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