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USE OF A HYDROGEN METAL HYDRIDE SYSTEM TO INCREASE GLASS PRODUCTION EFFICIENCY

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Today, the most effective means of using the energy potential of the secondary energy resources of industrial enterprises is the use of cogeneration utilization systems. This makes it possible to concurrently obtain both heat and electrical energy, and significantly reduce heat losses. This paper proposes that sheet glass producing enterprises use additional utilization systems for making use of heat from glass furnace gases. The current state of hydrogen use during glass production is analyzed. A scheme of energy technology complex with a hydrogen turbine and a metal hydride system for the combined production of heat and electric energy is developed. A calculation and theoretical study has been conducted to determine the main parameters of the hydrogen heat recovery system in the range of furnace gas temperatures from 523 to 673 K, as well as the efficiency of the system application. Using the developed mathematical model of the processes of heat and mass transfer in metal hydrides, we obtained data regarding the operating parameters of the thermosorption compressor, which allowed us to determine the structural characteristics of the metal hydride system as a whole. As a result of the calculation, we obtained coolant characteristics at hydrogen circuit key points, and determined the hydrogen turbine power. The electric energy produced in it can be used for the electrolyzer of the hydrogen station of an enterprise. The oxygen generated during the electrolysis process is added to the combustion air, which will increase the combustion temperature of the fuel mixture and increase glass furnace efficiency. Thus, a complex of proposed measures for the utilization of the energy potential of glass furnace gases will allow us to increase the energy efficiency of sheet glass production and the competitiveness of glass-producing enterprises.

Keywords: *glass production, energy technology complex, hydrogen, metal hydride system, heat and mass transfer processes.*

Introduction

Today, the most common way of utilizing the furnace gas thermal potential is to supplement the heat technology schemes of high-temperature plants with additional utilization units. This makes it possible to obtain, in addition to heated air, water steam, cold in absorption refrigeration units, electricity, or mechanical energy [1, 2].

From the point of view of a fuller utilization of the fuel energy potential, the most efficient way is to use cogeneration schemes. For closed cycles, thermodynamic efficiency depends to a large extent on the choice of the working fluid. In this case, quite a promising way for cogeneration plants is the use of hydrogen turbines [3]. Light gases have thermophysical properties that can minimize the mass and dimensions of the main elements of the process equipment included in power plants. This opens up prospects of creating high-efficiency turbines that have a number of significant advantages over traditional gas or steam turbine installations.

The presence of a hydrogen station and the corresponding infrastructure at sheet glass producing enterprises opens up the prospect of using hydrogen as a working fluid in the recycling circuit of an energy technology complex. Such enterprises use a float production method, where the process of forming a strip of glass on a molten metal takes place in a bath containing a layer of molten tin and a protective atmosphere consisting of nitrogen and a reducing gas, hydrogen. A typical float tank consumes an average of 1200–1500 Nm^3/h of nitrogen and 60–100 Nm^3/h of high purity hydrogen [4]. Hydrogen is produced by electrolyzers, where both hydrogen and oxygen are released in the process of water electrolysis. The hydrogen is then purified from the oxygen, which is carried out with the help of a palladium catalyst in a catalytic

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reactor. In addition, the hydrogen undergoes deep drying as well as purification from other impurities. It is then fed into gas holders and from there, into the melting bath.

Problem Formulation

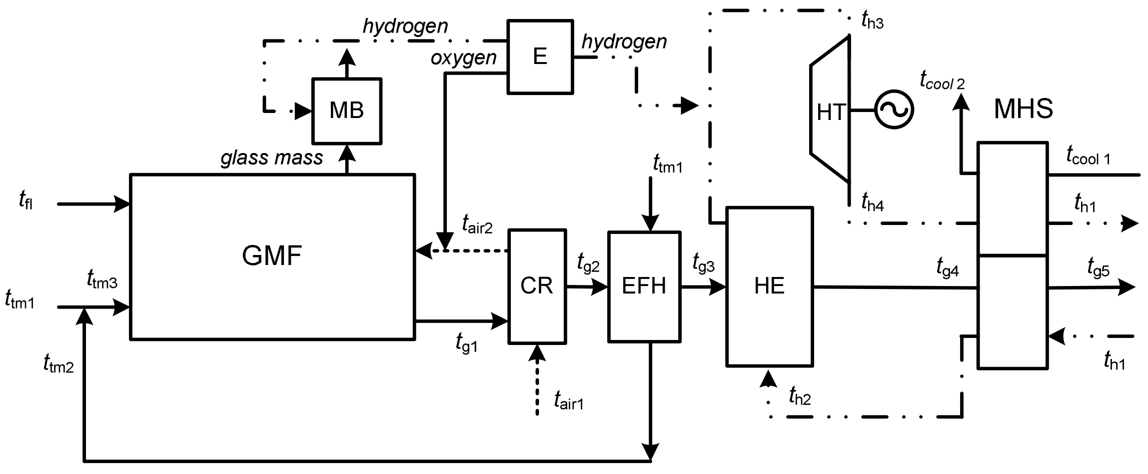
One of the problems with the use of hydrogen in turbines is the considerable cost of compressing it [5]. Therefore, it is advisable to use metal hydride technology for the direct conversion of heat into the energy of compressed hydrogen by means of a thermosorption compressor (TSC), with its principle of action based on the properties of metal hydrides (MH) to absorb hydrogen and release it at increased pressure under conditions of heat. The main advantage of the hydride hydrogen storage method is its compactness. With the same volumes, there is more hydrogen in MHs than in the liquid hydrogen contained in a cryogenic tank, due to the higher density of hydrogen in the solid phase compared to the liquid one. Thanks to this, a hydride battery can be arbitrary in shape, making it easier to use in power and process installations. Depending on the type of the hydride-forming material and external conditions, the sorption-desorption of hydrogen can be realized in extremely wide ranges of working pressures and temperatures, and significant thermal effects of the reaction lead to the fact that the sorption is accompanied by a significant heat dissipation, while desorption, by the cooling of the MH material. These circumstances are the basis of using MHs related to both energy transformation and control of thermal cycles and processes.

Study Major Part Outline

A general scheme of the power engineering system for a glass-making furnace with a hydrogen storage system and a turbo installation is shown in Figure.

The process of making glass is carried out in a recuperative glass making furnace (GMF) with a central recuperator (CR). The furnace receives charge and fuel (natural gas) with temperatures t_{tm1} and t_{fl}, respectively. The cullet (with temperature t_{tm1}) enters an electrical filter-heater (EFH), in which, due to the heat of the furnace gas, its temperature increases to t_{tm2}. Also, the gas is cleaned of the dust that settles on the cullet. Then the heated cullet is mixed with other materials of the charge and with temperature t_{tm3} is fed into the glass furnace. The combustion air, heated in the CR, is fed to a burner device with temperature t_{air2}.

The output streams are glass mass and furnace gases having temperature t_{g1}. The gases transfer some of the heat to the cullet and combustion air, are sent to a heat exchanger (HE), where the hydrogen from the metal hydride system (MHS), which includes a TSC, is heated from temperature t_{h2} to temperature t_{h3}. Also, in this system, the process of cooling the furnace gas from temperature t_{g4} to temperature t_{g4} takes place. Here, the hydrogen pressure increases to P_{h4}, and the temperature, to t_{h4}. Thus, the hydrogen compression process is carried out in the MHS, and the expansion process takes place in a hydrogen turbine (HT), where the hydrogen pressure is reduced to P_{h3}.



Scheme of the glass production power engineering complex with a metal hydride system

To obtain the hydrogen that will be used in the melting bath (MB), a hydrogen station with electrolyzers (E) and a purification system is used. The hydrogen also enters the utilizing part of the scheme consisting of a hydrogen storage system and an HT. After separation from the hydrogen, the oxygen is added to the combustion air to increase the combustion temperature in the glass-making furnace.

We performed calculations for a sheet glass-making furnace with a fuel consumption of 750 m^3/h. The amount of the furnace gas is 7.433 m^3/h. Let us analyze the operation of the hydrogen power plant in the temperature range of furnace gases T_{g3} from 523 to 673 K with an increment of 50 K. The scheme uses a hydrogen turbine unit and a metal hydride system with $LaNi_5H_{6,7}$ hydride, whose phase transition heat is q_s=15,500 kJ/kg. The furnace gas temperature at the outlet after the MHS compressor, T_{g5}, is 393 K. At the maximum furnace gas temperature T_{g3}, the temperature difference between them and the hydrogen $\Delta T_1=T_{g3}-T_{air3}$=100 K, the hydrogen temperature at point 1 – $T_{H3}=T_{g3}-\Delta T_1$. The temperature difference $\Delta T_2=T_{g5}-T_{H2}$. Temperature T_{H2} is equal to the sorption temperature at the corresponding hydrogen pressure.

The table below shows results for the case when the furnace gas temperatures at the MHS inlet change, provided their flow consumption is constant.

Basic operating parameters of a power plant with a metal hydride system

Parameter	Value			
	1	2	3	4
Furnace gas temperature at the MHS inlet T_{g3}, K	523	573	623	673
Hydrogen temperature T_{H2}, K	273	273	273	273
Amount of heat transferred to the hydrogen circuit Q, kW	434.1	604.5	776.8	951.8
Hydrogen pressure P_{H2}, MPa	2	2	2	2
Hydrogen pressure P_{H1}, MPa	0,78	0,48	0,29	0,2
Hydrogen temperature at the MHS inlet T_{H4}, K	323	311	297	293
Working fluid flow rate in the hydrogen circuit, kg/s	0.025	0.033	0.041	0.048
Hydrogen turbine capacity N_{HT}, kW	29.2	61.2	106.4	155.1

Further calculations were performed for the last variant of the scheme at T_{g3}=673 K and the working fluid flow rate 0.48 kg/s. This is due to the fact that the hydrogen turbine capacity in other variants is lower, which negatively affects the efficiency of the cogeneration equipment.

The IPMash of the NAS of Ukraine has developed a mathematical model of the thermosorptional interaction of hydrogen with a metal hydride. It was described by equations of heat and mass transfer for the case of the viscous mode of hydrogen filtration through the dispersed layer of the metal hydride. Unlike previously described, this model takes into account:

– convective transfer contribution to the total heat flux;

– equilibrium relationships describing the relationship between pressure, temperature, and hydrogen concentration in the metal hydride over the entire concentration range;

– chemical kinetics of sorption (desorption).

Such an approach best corresponds to the actual operating conditions of energy converting MH systems. At present, the model is implemented numerically as a Java-based application package for PC-compatible personal computers working in the Windows environment [6, 7].

The mathematical model of the heat transfer process in a MH takes the following form:

$$\frac{\partial T}{\partial \tau} = a_{\mathrm{MH}}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\beta c_{\mathrm{H_2}}}{c\rho} J \frac{\partial T}{\partial r}; \tag{1}$$

$$q_s \rho \frac{\partial \chi}{\partial \tau} = \lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) + \beta c_{\mathrm{H_2}} J \frac{\partial T}{\partial r}; \tag{2}$$

$$\chi(\Theta) = 2\ln\left(\frac{\Theta}{1-\Theta}\right) + \frac{\bar{H}_1(\Theta)}{RT}; \tag{3}$$

$$\frac{1}{\xi R_{\mathrm{H_2}}}\frac{\partial}{\partial \tau}\left(\frac{P\rho}{T}\right)=\frac{Jp}{r}+p\frac{\partial J}{\partial r}+J\frac{\partial p}{\partial r}-\rho\frac{\partial \chi}{\partial \tau}; \tag{4}$$

$$J=h\frac{P^3}{\mu}\frac{p}{\xi R_{\mathrm{H_2}}T}\frac{d_{\mathrm{avg}}{}^2}{(1-\Pi)^2}\frac{\partial p}{\partial r}; \tag{5}$$

$$\frac{d\chi}{d\tau}=A\cdot\frac{p(T,\chi)}{p_d(T,\chi)\cdot f_{spc}\cdot\Delta\tau\cdot\Delta\mu'}; \tag{6}$$

$$\left(p+\frac{a}{v^2}\right)(v-b)=R_{\mathrm{H_2}}T, \tag{7}$$

where a_{MH} is the hydride thermal conductivity coefficient; β is the correction factor; $c_{\mathrm{H_2}}$ is the hydrogen heat capacity coefficient; c is the hydride heat capacity coefficient; ρ is the hydride density; J is the hydrogen flux density; q_S is the thermal effect of the reaction of the thermochemical interaction of the hydride with hydrogen; λ is the thermal conductivity coefficient; Θ is the degree of filling the metal hydride matrix interstices with hydrogen atoms; $\bar{H}_1(\Theta)$ is the concentration dependence of the partial molar enthalpy of interaction between hydrogen atoms; P is the metal hydride porosity; ξ is the gas compressibility coefficient; h is the filtration coefficient; d_{avg} is the average equivalent diameter of a hydride particle; μ is the dynamic viscosity coefficient; p_d is the desorption pressure; f_{spc} is the specific surface area; μ' is the chemical potential; $A=\Delta G_0+RT\ln p$ is a complex value; ΔG_0 is the Gibbs energy change; v is the volume; a, b are the viral coefficients.

The system of equations (1)–(7) is closed by the initial and boundary conditions of the third kind.

Performing thermal engineering calculations of MH systems presupposes not only thermosorptional, but also thermophysical characteristics of the materials used. The available data on the thermophysical properties of metal hydrides are discontinuous and do not take into account a number of factors that are essential for the heat transfer processes during the interaction between a metal hydride and hydrogen. The absence of these data does not allow us to establish the dependence of thermophysical characteristics on the stage of the process in the real range of change of mode parameters, which introduces a significant error in the calculation results of the design of metal hydride elements.

One of the most effective ways of identifying thermophysical characteristics is to use instruments of inverse thermal conductivity problems, in particular, to determine the coefficients of effective thermal conductivity of metal hydrides and its dependence on the parameters of the process of interaction with hydrogen [8]. A mathematical model of heat and mass transfer in a metal hydride in a nonlinear formulation is conditioned by dependence of the MH thermophysical properties and structural characteristics on the parameters of the thermosorption process. Thus, in view of the above, a mathematical model of the interaction between hydrogen and metal hydrides is an effective tool to obtain data on the mode and design parameters of the MH system as part of the energotechnological glass making complex.

Providing the sorbent generator operation cyclicity is taken into account, it becomes clear that it will not be able to maintain the required hydrogen flow all the time [9]. The calculations performed showed that during operation on an asymmetric cycle, it is necessary to use four generators concurrently. Below are the basic design characteristics of the hydrogen storage system that were obtained using the methods of mathematical modeling of complex heat transfer processes in metal hydrides.

MH mass, kg	3136
MH volume, m^3	0.95
Sorber-generator body outer diameter , m	0.048
Sorber-generator body inner diameter, m	0.032
Overall length of sorber-generators, m	995
Length of a single sorber-generator, m	1.55
Total number of sorber-generators, pcs	656
Number of sorber-generator units (4 pcs in each), pcs.	164

The electrical energy produced in the hydrogen turbine can be used in an electrolytic cell to produce hydrogen that is used during the float process of sheet-glass making as a component of a protective atmosphere. The average specific energy consumption for the production of 1 m^3 of hydrogen in modern electrolizers is 4.3 kWh [5]. Then, at the power of the hydrogen turbine N_{HT}=155.1 kW, the amount of hydrogen produced will be 36.1 m^3/h, and that of oxygen, 18.05 m^3/h.

In the process of electrolysis, 1 m^3 of hydrogen receives 0.5 m^3 of oxygen that can be used as an oxidizer for natural gas in a glass-making furnace. The supply of pure oxygen makes it possible to increase the combustion temperature of the fuel by reducing the supply of nitrogen, which is part of the combustion air.

Thus, there is a possibility of reducing fuel consumption or increasing the furnace capacity while maintaining the consumption. Considering the first variant, there is a problem of infringing glass mass melting technology by reducing the amount of furnace gases in the furnace space. So let us consider the possibility of increasing the furnace glass-making capacity, while keeping the fuel consumption unchanged. For this purpose it is necessary to calculate the combustion temperature of natural gas for cases of supplying both atmospheric and oxygen-enriched air [10]. The amount of pure oxygen per 1 m^3 of natural gas is 0.024 m^3/m^3. The combustion temperature under the conditions of using atmospheric air is t_{g1}=2,291 °C, and that with the addition of oxygen is t_{g2}=2,315 °C. The increase in the furnace glass-making capacity is 209 t/year (0.99%). Electricity savings through the use of a hydrogen turbine are 1 247 164 kWh/year.

Conclusions

To utilize the energy potential of the furnace gases of a glass-making furnace, it is proposed to use an energy conversion complex with a hydrogen turbine and a metal hydride system. Using the methods of mathematical modeling, a computational-theoretical study was conducted to determine the basic operating parameters of the hydrogen heat recovery system in the range of furnace gas temperatures from 523 to 673 K. For the selected variant of the scheme, a calculation was performed to determine the efficiency of its application. According to the calculation results, the maximum capacity of the hydrogen turbine was 155 kW, and the electricity saved was 1,247 MW·h/year. A scheme of the MH system with four sorber-generators was selected, which provides a continuous supply of hydrogen in the amount of 0.048 kg/s. The total number of sorber-generators is 656 pieces with a total hydride weight of 3,160 kg. The use of the oxygen obtained during the electrolysis process, providing it is added to the combustion air, will increase the furnace productivity by 209 tons/year by increasing the combustion temperature of the fuel. Thus, the application of this scheme for the utilization of the potential of furnace gases will reduce the cost of glass production, while increasing its production, which will increase the competitiveness of glass-making enterprises.

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Використання водневої металогідридної системи для підвищення енергоефективності скловарного виробництва

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Найбільш ефективним засобом використання енергетичного потенціалу вторинних енергоресурсів промислових підприємств сьогодні вважається застосування когенераційних утилізаційних систем. Це дає змогу отримати одночасно теплову та електричну енергію та значно зменшити теплові втрати. У роботі запропоновано для підприємства з виробництва листового скла використання додаткової утилізаційної системи для використання теплоти димових газів скловарних печей. Проаналізовано сучасний стан використання водню під час виробництва скломаси. Розроблено схему енерготехнологічного комплексу з водневою турбіною та металогідридною системою для комбінованого вироблення електричної та теплової енергії. Проведено розрахунково-теоретичне дослідження з метою визначення основних параметрів роботи водневої теплоутилізаційної системи в діапазоні температур димових газів від 523 до 673 К, а також ефективності її застосування. З використанням розробленої математичної моделі процесів тепломасообміну в гідридах металів отримані дані щодо режимних параметрів роботи термосорбційного компресора, що дозволили визначити конструктивні характеристики металогідридної системи в цілому. В результаті проведеного розрахункового дослідження отримані характеристики теплоносія в ключових точках водневого контуру, визначено потужність водневої турбоустановки. Електрична енергія, що виробляється у ній, може бути використана для електролізера водневої станції підприємства. Кисень, який утворюється під час процесу електролізу, додається до повітря горіння, що дасть змогу підвищити температуру горіння паливної суміші та збільшити продуктивність скловарної печі. Таким чином, комплекс запропонованих заходів з утилізації енергетичного потенціалу димових газів скловарних печей дасть змогу підвищити енергоефективність виробництва листового скла та конкурентоспроможність скловарних підприємств.

Ключові слова: *скловарне виробництво, енерготехнологічний комплекс, водень, металогідридна система, тепломасообмінні процеси.*

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