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Mini CHP based on the electrochemical generator and impeded fluidized bed reactor for methane steam reforming☆

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ABSTRACT

The paper presents a configuration of mini CHP with the methane reformer and planar solid oxide fuel cell (SOFC) stacks. This mini CHP may produce electricity and superheated steam as well as preheat air and methane for the reformer along with cathode air used in the SOFC stack as an oxidant. Moreover, the mathematical model for this power plant has been created. The thermochemical reactor with impeded fluidized bed for autothermal steam reforming of methane (reformer) considered as the basis for the synthesis gas (syngas) production to fuel SOFC stacks has been studied experimentally as well. A fraction of conversion products has been oxidized by the air fed to the upper region of the impeded fluidized bed in order to carry out the endothermic methane steam reforming in a 1:3 ratio as well as to preheat products of these reactions. Studies have shown that syngas containing 55% of hydrogen could be produced by this reactor. Basic dimensions of the reactor as well as flow rates of air, water and methane for the conversion of methane have been adjusted through mathematical modelling.

The paper provides heat balances for the reformer, SOFC stack and waste heat boiler (WHB) intended for generating superheated water steam along with preheating air and methane for the reformer as well as the preheated cathode air. The balances have formed the basis for calculating the following values: the useful product fraction in the reformer; fraction of hydrogen oxidized at SOFC anode; gross electric efficiency; anode temperature; exothermic effect of syngas hydrogen oxidation by air oxygen; excess entropy along with the Gibbs free energy change at standard conditions; electromotive force (EMF) of the fuel cell; specific flow rate of the equivalent fuel for producing electric and heat energy. Calculations have shown that the temperature of hydrogen oxidation products at SOFC anode is 850 °C; gross electric efficiency is 61.0%; EMF of one fuel cell is 0.985 V; fraction of hydrogen oxidized at SOFC anode is 64.6%; specific flow rate of the equivalent fuel for producing electric energy is 0.16 kg of eq.f./(kW·h) while that for heat generation amounts to 44.7 kg of eq.f./(GJ). All specific parameters are in agreement with the results of other studies.

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Nomenclature

Acronyms

ECG	Electrochemical generator
EMF	Electromotive force
eq.f.	Equivalent fuel
FRR	Flow rate ratio
CHP	Cogeneration plant
SOFC	Solid oxide fuel cells
Syngas	Synthesis gas
WHB	Waste heat boiler

Greek Letters

α	Excess air factor
η	ECG gross efficiency
φ	Fraction of the reacted reagent

Latin Letters

B	Syngas flow rate
c	Isobaric specific heat capacity, kJ/(K·kg)
E	EMF of one planar element, V
F	Faraday constant, $9.648 \cdot 10^4$ C/mol
G	Flow rate of heat carriers differing from syngas, kg/s
ΔG	Gibbs energy change, kJ/kg, kJ/kmol of water
ΔH	Heat of reaction, kJ/(K·kg of syngas)
h	Steam enthalpy, kJ/kg
q	Heat loss, kJ/kJ
Q	ECG power, kW
ΔS	Excess entropy of the reaction, kJ/(K·kg of syngas)
t	Temperature, °C

Superscripts and Subscripts

a	Air
E	Electrical quantity
ECO	Steam at the economizer outlet
cp	Combustion products
H_2O	Water steam in the reformer
M	Methane
out	Flue gases at the WHB outlet
S	Hydrogen oxidized at the anode
sg	Syngas
ss	Superheated steam at the WHB outlet
1	Hydrogen oxidation in syngas (ΔH)
2	Carbon monoxide oxidation in syngas (ΔH); air in the cathode channel
3	Incomplete combustion (q); syngas in the anode channel (t)
4	Air at the reformer inlet (t)
5	External heat loss through barriers
*	Anode channel inlet (c_{sg}); cathode channel inlet (c_a, G_a); reformer inlet (t_M); anode channel outlet (B_{sg}, t_3); WHB outlet (c_M); cathode channel outlet (t_2)
**	Anode channel outlet (csg); cathode channel outlet (c_a, G_a)
***	For the reformer at WHB outlet
0	Standard conditions

Introduction

One of the trends in modern electric power industry which allows increasing the efficiency of the electricity production from hydrocarbon fuel as well as reducing carbon emissions may be the development of power plants based on electrochemical generators (fuel cells) [1,2]. The reactor for producing hydrogen along with the fuel cell stack is the key elements of such plants. Solid oxide fuel cells (SOFC) may be the most advanced due to the air used as oxidizer and syngas (which could contain CO along with hydrogen) used as fuel in them [3]. Syngas is usually produced by conversion of methane [4,5] or coal [6,7] in reactors through a catalyst in the form of a granular bed or structured surfaces [8–10]. The syngas and air in the anode and cathode channels of planar composite SOFC stacks flow transversely [11,12].

The paper considers a configuration of the fuel cell power plant with impeded fluidized bed reactor for autothermal steam reforming (reformer) of methane by a dispersed heat carrier of the original design which could be used to create reactors producing hydrogen for high-capacity power plants. Specific fuel flow rates for producing electric and heat energy have been determined according to the proposed configuration as well as the comparison of this data with the performance of modern steam power plants has been carried out. The temperature of the methane reformer along with the fraction of hydrogen oxidized at the anode as well as EMF and electric efficiency of the planar SOFC stack has been determined to analyze the efficiency of the configuration components.

Theory

Chemical reactions proceeding in the configuration compounds have been considered as well as heat balance equations have been set up while calculating parameters of the power plant configuration [13,15]. The following equations may be considered as basic equation models for calculating the proposed cogeneration plant:

1) Heat balance equation for the reformer with partial oxidation of conversion products with a view to ensuring autothermal operation (determines a fraction of combusted syngas required to reach the defined temperature in the reactor);
2) Heat balance equation for the fuel cell to determine a fraction of hydrogen oxidized at the anode;
3) Power balance equation for WHB to determine external heat loss with outgoing gases;
4) Equation for calculating the specific fuel rate to produce electric and heat energy.

The successive solution of the equations described may allow calculating the temperature and flow rate of gases in configuration components of the power plant.

Description of the power plant configuration

The power plant configuration is shown in Fig. 1.

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