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A research on hydrogen production from industrial waste heat by thermal water splitting

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ABSTRACT

Energy is the most important issues of social and economic life in countries either developed or just developing. It is very well known that hydrogen energy, which is the most advanced energy carrier; environmental friendly and sustainable, can compensate the increasing energy requirements. The generation of hydrogen through electrolysis possessed several advantages, such as high efficiency, low pollutant emissions and flexible fueling strategies. This research aims to create an efficient, effective and multi-disciplinary solution package to produce hydrogen evaluating the waste heat. The main goal of this research was to increase the efficiency of hydrogen production by operating the Solid Oxide Electrolysis Cell (SOEC) at an optimum combination of operating conditions. Number of electrolysis cell, the number of stacks and cell area which are the parameters that affect the high temperature electrolysis are determined on the basis of previous studies. Steam temperature and steam flow rate that are calculated parametrically for the system.

Introduction

One of the new emerging technologies having the world's clean energy choice is based on hydrogen. Flexible, affordable, safe, domestically produced, usable in all sectors of the economy and in all regions of the country; hydrogen may play an important role as an energy carrier of the future [1].

There is a growing interest in the development of large-scale non-fossil hydrogen production technologies [2]. This interest is driven by the immediate demand for hydrogen for refining of increasingly low-quality petroleum resources [2–4], the expected intermediate term demand for carbon-neutral synthetic fuels [2,5], and the possible long-term demand for carbon-free hydrogen as an environmentally benign transportation fuel [2,6].

Hydrogen technology, as an environmental friendly technology, has advantages. It is considered as a universal energy carrier for the future. Large-scale hydrogen production without fossil consumption and various gas emissions such as CO_x, SO_x and NO_x is the key to achieving the Hydrogen Economy [7–14]. Hydrogen can produce with water electrolysis [14–18], thermochemical cycles [14,19,20] and photo catalysis processes [21–23]. These methods are non-fossil fuel based process.

Until now, probably the cleanest method of producing hydrogen has been water electrolysis [14]. Electrolysis process is much more efficient at raised temperatures [24,25]. Temperature is known to be one of the most effective variables on the electric power demand of an electrolysis cell. The reasons of this behavior can be discussed according to the thermodynamic characteristics of a water molecule, as its splitting

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reaction potential is known to reduce as the temperature increases. Moreover, ionic conductivity and surface reaction of an electrolyte rise directly with temperature [25,26]. High temperature water electrolysis requires less energy to reach any given current density in analogy with a low temperature process [25,27,28].

Theoretically, the efficiency of a solid oxide electrolysis cell improved with increased temperature as a result of reduction in the Gibbs free energy change [29]. In this field, Solid Oxide Electrolysis Cells (SOEC) have attracted a great interest in the last few years, as they offer significant power and higher efficiencies compared to conventional low temperature electrolyser [14].

This research aims to create an effective solution package to produce hydrogen evaluating the waste heat. In this research, the idea is to improve hydrogen production efficiency through a solid oxide electrolysis process with waste heat. It is investigated to recovery the portion of the heat and to convert to useful work released into the atmosphere by flue gases. Values that can vary according to the materials and manufacturability of hydrogen are analyzed. Flue gas exit temperature which is the main factor for steam temperature and steam flow rate dependence on the factors affecting the thermal electrolysis is analyzed for the designed system.

Material and methods

Flue gas released to the atmosphere from an industrial plants' chimneys causes internal heat pollution. This research is investigated to recovery the portion of the heat and to convert to useful work released into the atmosphere by flue gases. All data used in the analysis of waste heat are all an industrial plants' real data. Research for the design and analysis is performed parametrically. The solution package which will be created for the purpose of the thesis consists of two main processes: The first process is to catch the waste heat with a heat exchanger. In this process, design limits are determined by an acceptable pressure drop of fluid and the total amount of heat that can be transferred. At this point, heat exchangers are investigated that are available on market and heat exchanger that provides the package has been designed on. However, heat transfer capacity and pressure loss of heat exchangers which are available on market are not within acceptable limits for our solution package.

The second process is to produce hydrogen using high-temperature steam electrolysis. Captured heat in the first process provides the heat of the electrolysis. In this process, the geometry of the electrode and material are focused on fundamental issues. In this process, the efficiency of the different options and economic analysis is performed. This situation makes it adaptable solution package. Parameters that affect the operation of the solid oxide electrolysis cells are area specific resistance, steam utilization, electrolysis voltage, thermoneutral voltage, current density, number of electrolysis cell and number of stack. Steam temperature and steam flow rate that are calculated parametrically. Flue gas exit temperature which is the main factor for steam temperature and steam flow rate dependence on the factors affecting the thermal electrolysis is analyzed for the designed system (see Fig. 1).

Calculation

Principles of electrolysis

Water electrolysis is an endothermic chemical reaction through which the molecule can be split into hydrogen and oxygen when a certain amount of electricity and heat are supplied [5]. The chemical reaction is presented in Equation (1);

$$H_2O \rightarrow 1/2H_2 + O_2 \tag{1}$$

When a potential applies to electrodes in an electrolysis cell, electrode reaction in Equations 2 and 3;

Cathode Reaction:

$$2H_2O_{(s)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)} \tag{2}$$

Anode Reaction:

$$OH^-_{(aq)} \rightarrow H_2O_{(s)} + 2e^- + \frac{1}{2}O_{2(g)} \tag{3}$$

A basic thermodynamic analysis can be applied to a general thermal water-splitting process in order to determine the overall process efficiency limits as a function of temperature. Consider the control volume diagram which water enters it in the liquid phase at some temperature T and pressure P and pure hydrogen and oxygen streams exit the control volume also at T and P. Two heat reservoirs are at temperature T_H and a low-temperature reservoir at temperature T_L. Heat transfer between these reservoirs and the control volume is indicated in the figure as Q_H and Q_L. Note that there is no work crossing the control-volume boundary. Therefore if the process under consideration is high temperature, the electrolyser is located inside the control volume [2].

The first and second laws of thermodynamics can be applied to this process as follows:

$$1^{st}\ \text{law}:\ Q_H - Q_L = \Delta H_R \tag{4}$$

$$2^{nd}\ \text{law}:\ \Delta S_R \geq \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \tag{5}$$

ΔH_R is the enthalpy of reaction and ΔS_R is the entropy change of the reaction.

The high-temperature heat requirement for the process can be stated as:

$$Q_H \geq \frac{T_H}{(T_H - T_L)}\left(-\Delta G^0_{h,H_2O}\right) \tag{6}$$