

Available at [www.sciencedirect.com](http://www.sciencedirect.com)journal homepage: [www.elsevier.com/locate/hydro](http://www.elsevier.com/locate/hydro)

# Thermodynamic analysis of models used in hydrogen production by geothermal energy

Mehmet Kanoglu<sup>a,\*</sup>, Ali Bolatturk<sup>b</sup>, Ceyhan Yilmaz<sup>a</sup>

<sup>a</sup> Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey

<sup>b</sup> Department of Mechanical Engineering, Suleyman Demirel University, 32260 Isparta, Turkey

## ARTICLE INFO

### Article history:

Received 26 March 2010

Received in revised form

24 May 2010

Accepted 26 May 2010

### Keywords:

Hydrogen production

Hydrogen liquefaction

Geothermal energy

Binary cycle

Precooled Linde–Hampson cycle

## ABSTRACT

Four models are developed for the use of geothermal energy for hydrogen production. These include using geothermal work output as the work input for an electrolysis process (Case 1); using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water (Case 2), using geothermal heat to preheat water in a high-temperature electrolysis process (Case 3), and using part of geothermal work for electrolysis and the remaining part for liquefaction (Case 4). These models are studied thermodynamically, and both reversible and actual (irreversible) operation of the models are considered. The effect of geothermal water temperature on the amount of hydrogen production per unit mass of geothermal water is investigated for all four models, and the results are compared. The results show that as the temperature of geothermal water increases the amount of hydrogen production increases. Also, 1.34 g of hydrogen may be produced by one kg of geothermal water at 200 °C in the reversible operation for Case 1. The corresponding values are 1.42, 1.91, and 1.22 in Case 2, Case 3, and Case 4, respectively. Greater amounts of hydrogen may be produced in Case 3 compared to other cases. Case 2 performs better than Case 1 because of the enhanced use of geothermal resource in the process. Case 4 allows both hydrogen production and liquefaction using the same geothermal resource, and provides a good solution for the remote geothermal resources. A comparison of hydrogen production values in the reversible and irreversible conditions reveal that the second-law efficiencies of the models are 28.5%, 29.9%, 37.2%, and 16.1% in Case 1, Case 2, Case 3, and Case 4, respectively.

© 2010 Professor T. Nejat Veziroglu. Published by Elsevier Ltd. All rights reserved.

## 1. Introduction

Geothermal energy is the thermal energy within the earth's interior. Geothermal energy is used to generate electricity and for direct uses such as space heating and cooling, industrial processes, and greenhouse heating. High-temperature geothermal resources above 150 °C are generally used for power generation. Moderate- (between 90 °C and 150 °C) and low-temperature (below 90 °C) geothermal resources are best suited for direct uses such as space and process heating,

cooling, aquaculture, and fish farming [1]. With the increasing scarcity of fossil fuels and increasing concerns over the environmental problems they cause, the use of renewable energy resources will likely increase and diversify. Geothermal energy appears to be a potential solution where it is available to some of the current energy and environmental problems, and a key resource for making society more sustainable [2].

Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy.

\* Corresponding author. Tel.: +90 342 3604008; fax: +90 342 3601104.

E-mail address: [kanoglu@gantep.edu.tr](mailto:kanoglu@gantep.edu.tr) (M. Kanoglu).

0360-3199/\$ – see front matter © 2010 Professor T. Nejat Veziroglu. Published by Elsevier Ltd. All rights reserved.

doi:10.1016/j.ijhydene.2010.05.128

Geothermal power plants tap certain high-temperature resources to generate electricity with minimal or no air emissions. The common types of geothermal power plants are dry steam, single- and double-flash, binary, and flash/binary cycles.

Hydrogen is considered by many to be a potential replacement for fossil fuels [3]. The total cost of producing hydrogen depends on production, liquefaction, storage and distribution costs [4]. Sherif et al. [5] provides some key data on economics of hydrogen production.

There are several methods used to produce hydrogen. These methods include: steam methane reforming (SMR), electrolysis, coal gasification, liquid reforming, nuclear high-temperature electrolysis, high-temperature thermo-chemical water-splitting, photo-biological, and photo-electrochemical. The first three methods are currently used while the remaining ones are still being researched or developed. Electrolysis is a method of using an electric current to drive an otherwise non-spontaneous chemical reaction. Electrolysis is the passage of an electric current through an ionic substance that is either molten or dissolved in a suitable solvent, resulting in chemical reactions at the electrodes and separation of materials [6].

Currently, 80–85% of the world's total hydrogen production is derived via steam methane reforming of natural gas. Most of the remaining hydrogen production is accomplished via coal gasification and water electrolysis (at a smaller scale) [7]. Hydrogen production requires the investment of energy and capital. At present only the space industry uses hydrogen as fuel in large quantities. These industrial methods mainly consume fossil fuels as energy source and are considered to be energy intensive and not always environmental friendly [8,9].

A number of existing and planned demonstration projects are using or will use electrolysis, even though it is one of the more energy intensive processes for producing hydrogen. However, it provides a pathway for producing hydrogen from carbon free renewable energy. Hydrogen provides the connecting point between renewable electricity production and transportation, stationary and portable energy needs. When the electricity from solar photovoltaics, wind, geothermal, ocean and hydro technologies is used to produce and store hydrogen, the renewable source becomes more valuable and can meet a variety of needs [10].

Jonsson et al. [11] investigated the feasibility of using geothermal energy for hydrogen production and estimated that using geothermal energy could avoid 16% of the work consumption for electrolysis and 2% for liquefaction. Sigurvinsson et al. [12] investigated the use of geothermal heat in high-temperature electrolysis (HTE) process. This HTE process includes heat exchangers and an electrolyser based on solid oxide fuel cell (SOFC) technology working in inverse, producing oxygen and hydrogen instead of consuming them. Using features related to the heat exchangers and the electrolyser, a set of physical parameters were calculated by using a techno-economic optimization methodology.

Mansilla et al. [13] studied a techno-economic optimization of the upper heat exchanger network in the high-temperature electrolysis process for producing hydrogen. Heat obtained by coupling the process either to a high-temperature reactor or to a geothermal source. Ingason et al. [14] investigated the most economical ways of producing hydrogen solely via electrolysis

from water, using electricity from hydro and geothermal power. The mixed integer programming model presented here facilitates the search for optimal choices from the 23 potential power plants, 11 of which are based on geothermal sources, and 12 are hydropower stations. The potential of geothermal resources of the western United States for producing electricity is investigated. This electricity would be used for the production of hydrogen [15]. Balta et al. [16] analyzed high-temperature electrolysis process where geothermal water is used as the heat source. The same group [17] investigated various options for geothermal-based hydrogen production systems and their technical, operational and efficiency aspects.

Kanoglu et al. [18] investigated the use of geothermal energy for hydrogen liquefaction. Three models were considered for the analysis including the use of geothermal power for liquefaction cycle, the use of absorption cooling system for precooling gas before liquefaction and a cogeneration option for which both geothermal electricity and geothermal heat for absorption system are used. The cogeneration option appeared to provide significant savings in the energy requirement in the liquefaction process.

Despite the existence of numerous investigations on the use of renewable energy sources for hydrogen production, reports on using geothermal energy sources for hydrogen production and liquefaction are limited as summarized above. The present paper differs from the previous work in literature as it introduces new models for using geothermal energy for hydrogen production. It also extends and complements the study by Kanoglu et al. [18] in which the models related to hydrogen liquefaction were considered. The models proposed in this paper include the following four cases: Case 1: Using geothermal work output as the work input for an electrolysis process. Case 2: Using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water. Case 3: Using geothermal heat to preheat water in a high-temperature electrolysis process. Case 4: Using part of geothermal work for electrolysis and the remaining part for liquefaction.

---

## 2. System descriptions

Four models are developed for the use of geothermal energy for hydrogen production (Fig. 1). These models: Case 1: Using geothermal work output as the work input for an electrolysis process (Fig. 1a). Case 2: Using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water (Fig. 1b). Case 3: Using geothermal heat to preheat water in a high-temperature electrolysis process (Fig. 1c). Case 4: Using part of geothermal work for electrolysis and the remaining part for liquefaction (Fig. 1d).

For the non-ideal (e.g., irreversible) operations of the four cases considered, we consider a binary geothermal power plant with isobutane as the working fluid as shown in Fig. 2. This is usually the choice of cycle for liquid-dominated geothermal resources. In this cycle, isobutane is heated and vaporized in the heat exchanger by geothermal water. Then, it flows through the turbine, is condensed and pumped back to the heat exchanger, completing the binary cycle. The heat

متن کامل مقاله

دریافت فوری ←

**ISI**Articles

مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات