Available online at www.sciencedirect.com
ScienceDirect
International Journal of Hydrogen Energy 32 (2007) 4250–4257
International Journal of HYDROGEN ENERGY
www.elsevier.com/locate/ijhydene

Geothermal energy use in hydrogen liquefaction

Mehmet Kanoglu[a,1], Ibrahim Dincer[b,*], Marc A. Rosen[b]

[a]Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey
[b]Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ont., Canada L1H 7K4

Received 23 May 2007; received in revised form 8 June 2007; accepted 8 June 2007
Available online 8 August 2007

Abstract

We propose the use of geothermal energy for hydrogen liquefaction, and investigate three possible cases for accomplishing such a task including (1) using geothermal output work as the input for a liquefaction cycle; (2) using geothermal heat in an absorption refrigeration process to precool the gas before the gas is liquefied in a liquefaction cycle; and (3) using part of the geothermal heat for absorption refrigeration to precool the gas and part of the geothermal heat to produce work and use it in a liquefaction cycle (i.e., cogeneration). A binary geothermal power plant is considered for power production while the precooled Linde–Hampson cycle is considered for hydrogen liquefaction. A liquid geothermal resource is considered and both ideal (i.e., reversible) and non-ideal (e.g., irreversible) system operations are analyzed. A procedure for such an investigation is developed and appropriate performance parameters are defined. Also, the effects of geothermal water temperature and gas precooling temperature on system performance parameters are studied. The results show that there is a significant amount of energy savings potential in the liquefaction work requirement as a result of precooling the gas in a geothermal absorption cooling system. Using geothermal energy in a cogeneration scheme (power production and absorption cooling) also provides significant advantages over the use of geothermal energy for power production only.

Keywords: Geothermal energy; Hydrogen liquefaction; Binary cycle; Absorption cooling; Precooled Linde–Hampson cycle

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 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. Other advantages of geothermal energy systems are that they are simple, safe, modular and adaptable. These advantages make them an attractive option to replace fossil fuels for both developed and developing countries [2]. A large fraction of the world's high-temperature geothermal resources have already been exploited for the generation of electricity. Of the geothermal resources above 90 °C, only about a quarter are at 150 °C or higher [3].

For most moderate-temperature geothermal resources, electricity generation is not economic due to the very low thermal efficiencies. However, geothermal energy is more effective when used directly than when converted to electricity since the direct use of geothermal heat in such processes as heating and cooling can replace the burning of fossil fuels from which electricity can be generated much more efficiently. An economic analysis of different uses of geothermal energy shows that heating or cooling can generate about three times as much revenue as power production [4]. But the use of geothermal energy faces challenges, since many geothermal resources are found in

* Corresponding author.
E-mail address: ibrahim.dincer@uoit.ca (I. Dincer).
[1] Worked as a visiting associate professor at University of Ontario Institute of Technology.

0360-3199/$ - see front matter
doi:10.1016/j.ijhydene.2007.06.006

Nomenclature

COP	coefficient of performance
c	specific heat, kJ/kg K
f	fraction
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
q	heat transfer per unit mass, kJ/kg
s	specific entropy, kJ/kg K
P	pressure, kPa
R	gas constant, kJ/kg K
T	temperature, °C or K
T_0	ambient temperature, °C or K
w	work per unit mass, kJ/kg
x	quality
y	mass liquefied per unit mass of geothermal water
z	mass of gas cooled per unit mass of geothermal water

Greek letters

η	efficiency

Subscripts

act	actual
comp	compressor
f	saturated liquid state
gen	generator
geo	geothermal
in	inlet state
iso	isobutane
II	second-law
liq	liquefaction
out	outlet state
pp	pinch-point
vap	vaporization
rev	reversible
s	source
1, 2, 3, ...	state numbers

remote locations and it is not economic to transport geothermal heat for significant distances over populated or industrial areas for space and process heating or cooling. Geothermal resources can be used for power generation and/or for suitable on-site applications.

Geothermal energy may be used for cooling in an absorption refrigeration cycle. Lithium bromide/water chillers are suited for space cooling applications while ammonia/water systems provide industrial cooling to as low as $-50\,^{\circ}\mathrm{C}$ [5]. Such refrigeration systems and applications are extensively discussed in [6]. At least two geothermal absorption cooling applications are in operation in the U.S. [7].

The liquefaction of gases is an important area of refrigeration since many important scientific and engineering processes at cryogenic temperatures depend on liquefied gases. Perhaps, the most common application of liquefaction involves the production of liquefied natural gas to facilitate its transport over long distances in insulated tanks [8].

Hydrogen is considered by many to be a potential replacement for fossil fuels [9]. The total cost of producing hydrogen depends on production, liquefaction, storage and distribution costs [10]. Hydrogen liquefaction systems have been the subject of many investigations (e.g., [11,12]). Despite the existence of numerous of investigations on the use of renewable energy sources for hydrogen production, reports on using renewable energy sources for hydrogen liquefaction are very limited. Jonsson et al. [13], for example, 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. To the best of the authors' knowledge, no reports on the use of geothermal energy for hydrogen liquefaction exist in the open literature.

In this paper, we propose the use of geothermal energy for hydrogen liquefaction, and investigate three possible cases: (1) using geothermal power as the input for a liquefaction cycle, (2) using geothermal heat in an absorption refrigeration process to precool hydrogen gas before it enters a liquefaction cycle; and (3) using part of the geothermal heat for absorption refrigeration to precool the gas and part of geothermal heat to produce power for use in the liquefaction cycle (i.e., cogeneration). We investigate these three cases considering both ideal (i.e., reversible) and non-ideal (e.g., irreversible) operations. As exergy methods can provide numerous benefits for understanding processes [14], exergy interpretations are provided where appropriate to enhance the discussion.

2. Analysis

In this section we consider both ideal (reversible) and non-ideal (irreversible) operations for performance analysis and comparison purposes.

2.1. Analysis with reversible operations

The maximum specific work that can be obtained by a geothermal power plant utilizing a resource at temperature T_s in an environment at T_0 is given by

$$w_{\mathrm{rev,out,geo}} = c(T_s - T_0) - T_0 c \ln\left(\frac{T_s}{T_0}\right), \quad (1)$$

where c is the specific heat of liquid water. Geothermal water is assumed an incompressible liquid. The coefficient of performance (COP) of a reversible absorption refrigeration unit may be expressed as [15]:

$$\mathrm{COP_{rev}} = \frac{q_L}{q_{\mathrm{gen}}} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right), \quad (2)$$