Nuclear Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Cogeneration of electricity and liquid fuels using a high temperature gas-cooled reactor as the heat source

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ARTICLE INFO

Keywords:
High temperature gas-cooled reactor
Cogeneration
Greenhouse gas
Energy economics
Job creation

ABSTRACT

A thermal-hydraulic model of high temperature gas-cooled reactor used for cogeneration of electricity and liquid transportation fuels was developed using Aspen HYSYS. The model transfers heat through: (1) a steam generator to a supercritical Rankine cycle producing electricity, and (2) an intermediate heat exchanger to a biomass gasifier and Fischer-Tropsch process producing gasoline, jet fuel, diesel, liquefied petroleum gas and/or naphtha. The individual systems and components in the cogeneration model are mature technologies and commercially available, because minimizing the need for additional innovation increases the overall probability of success for a new and unique hybrid system. Technical evaluations of cogeneration on the island of Oahu in the State of Hawaii, using eucalyptus and sugarcane as the biomass feedstock, indicated that high thermal efficiency was achievable and that the concept is technically viable. Economic evaluations of cogeneration, based on construction and finance costs and current electricity and liquid fuel prices, indicated that the cogeneration plant is economically viable. Additional analyses quantified the potential number of jobs created and the reduction in carbon emissions. Further analyses indicated that cogeneration would significantly enhance Hawaii's energy security.

1. Introduction

A thermal hydraulic model of a high temperature gas-cooled reactor (HTGR) used for integrated production (termed cogeneration) of electricity and liquid transportation fuels was developed using Aspen HYSYS. The integrated plant consisted of two HTGRs transferring heat through:

- a steam generator (SG) to a supercritical Rankine cycle (SCRC) producing electricity for use on the grid,
- an intermediate heat exchanger (IHX) to a biomass gasifier and Fischer-Tropsch (FT) process producing gasoline, jet fuel, diesel, liquefied petroleum gas (LPG) and/or naphtha.

The biomass gasifier and FT process were represented as nuclear heat and electric power loads coupled to the reactor through heat exchangers and turbine generators. High temperature steam from the HTGR was used to gasify the biomass. Electricity was also produced from waste heat in varied FT exhaust streams. The FT process was not specifically modeled in this analysis, but the loads and products were based on an Aspen Plus model developed by the Next Generation Nuclear Plant (NGNP) Project.

2. Background

There are no indigenous fossil fuels in the State of Hawaii and its citizens rely on imported petroleum for virtually all of their liquid transportation fuels. Natural gas prices in Hawaii are an order of magnitude higher than on the mainland, and as a result, over 90% of Hawaii's electricity is produced by combusting imported petroleum and coal. Combustion of petroleum is relatively inefficient. A major cost factor in the production of electricity from coal is transport distance and the majority of Hawaii's coal is shipped from Indonesia and Australia. Consequently, Hawaii's electricity prices are the highest in the nation.

In April 2016, the average residential cost of electricity in Hawaii was $269.3/MWhe and the average of all sectors was $226.8/MWhe, despite current low crude oil prices. Electricity prices in Hawaii are volatile, and residential prices have been over $400/MWhe for substantial periods in the last five years (U.S. Energy Information Administration, 2016).

Abbreviations: HTGR, high temperature gas-cooled reactor; SG, steam generator; SCRC, supercritical Rankine cycle; IHX, intermediate heat exchanger; FT, Fischer-Tropsch; LPG, liquefied petroleum gas; NGNP, Next Generation Nuclear Plant; GHG, greenhouse gas emissions; RIT, reactor inlet temperature; ROT, reactor outlet temperature; PCU, power conversion unit; HDBEDT, Hawaii Department of Business, Economic Development and Tourism; TCI, total capital investment; ROI, return on investment; FOAK, first-of-a-kind; NOAK, Nth-of-a-kind; MWe, megawatts electric; MWhe, megawatt-hours electric; MWt, megawatts thermal; MWht, megawatt-hours thermal; η_{th}, thermal efficiency; $\dot{W}$, work (MW); $\overline{Q}$, heat (MW)

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https://doi.org/10.1016/j.nucengdes.2018.01.029
Received 26 April 2017; Received in revised form 11 January 2018; Accepted 19 January 2018
0029-5493/

Coincidentally, Hawaii has the capacity to produce large quantities of biomass for the production of liquid fuels. Sugar cane production fell dramatically over the last several decades and hence, there are nearly 100,000 acres available for sugarcane production. Similar acreage is available for eucalyptus production.

These conditions suggest that cogeneration of electricity and liquid transportation fuels may be viable in Hawaii, and that investigation of liquid transportation fuel production using the heat of an HTGR is warranted. Past investigations of nuclear hybrid energy systems (Chen, 2016; Carlsson, 2014) indicate that configurations of this type are technically feasible for volatile market conditions and requiring flexible operations. Cogeneration from the HTGR could provide heat and electricity to the biomass processes; excess electricity could be sold to the Hawaiian grid. That is the subject of this paper.

3. Overview of the evaluation process

Three processes, combined in an integrated, hybrid system were modeled. Model development started with HTGR technology selection and definition of the nuclear island. Second, biomass conversion technologies were evaluated and specific technologies were selected. Last, a power conversion system was selected for electricity production.

After the three major systems were selected, a reference configuration was established and economic evaluations performed using tools developed by the Next Generation Nuclear Plant (NGNP) Project. The NGNP economic calculator was modified to integrate capital costs, operating costs, and revenue from liquid fuels production. After analyzing cogeneration economics for the reference configuration, the following additional analyses were performed:

- reductions in greenhouse gas emissions (GHG) were calculated,
- the number and type of jobs created were estimated, and
- the impact on energy security was evaluated.

4. Cogeneration model description

A preference for "close-to-market," or mature, technologies was adopted because the individual systems have not been combined in a hybrid cogeneration system before. Minimizing the need for innovation increases the overall probability for success in establishing a new and unique hybrid system.

4.1. Reactor island

Prismatic and pebble bed HTGRs have been built and operated previously, and are of similar technical maturity. The type of core is not a significant discriminator for the analyses performed in this study, and because design and cost data for a prismatic design were readily available, a prismatic core was chosen. For thermal power ratings, prismatic designs are generally bounded by the 600 MWt Gas-Turbine Modular Helium Reactor design developed by General Atomics. Therefore, the following parameters were defined for a prismatic HTGR reactor island:

- two reactors with heat output of 600 MWt per reactor,
- two loops for each reactor – one for liquid fuels production with an intermediate heat exchanger (IHX), the second for electricity production with a steam generator (SG),
- reactor outlet temperature (ROT) of 750 °C and reactor inlet temperature (RIT) of 322 °C,
- helium circulator(s) on the reactor cold leg(s) with isentropic efficiency of 75%,
- differential approach temperatures and pinch temperatures consistent with NGNP steam plant designs and with accepted, mature steam plant parameters (The Babcock and Wilcox Company, 2005),
- maximum steam temperature and pressure supplied to the PCU limited by the ASME limits for 800H, which is the alloy assumed for SG construction, and
- each PCU was sized to operate at full reactor power.

4.2. Liquid fuels production

Biomass conversion to liquid fuels is a proven, commercial activity that is possible using several different technologies, of which there are three prevailing types:

1. physical-chemical conversion,
2. bio-chemical conversion, and
3. thermo-chemical conversion.

The State of Hawaii Department of Business, Economic Development and Tourism (HDBEDT) determined that sugarcane was the most promising potential source of biomass (Keffer, 2006), and identified about 62,000 acres of available and irrigable land on Oahu for sugarcane production. It identified about 87,000 acres on Oahu suitable for the growth of eucalyptus as a secondary biomass source. The recommendations of the HDBEDT study were based on irrigation history and adequate annual rainfall statistics, and were accepted without further detailed analysis.

Physical-chemical and bio-chemical conversion of biomass were eliminated because they do not require the temperatures produced by an HTGR or because they do not work well with eucalyptus. Therefore, thermo-chemical conversion was selected as the technology for modeling liquid fuels production. Thermo-chemical conversion can be applied to nearly any biomass, but it is particularly well suited for this application because of the temperature match with the HTGR.

4.3. Synthetic gas production from biomass gasification

Gasified reformation of biomass is a type of thermo-chemical biomass conversion and is a more mature technology than pyrolysis or liquefaction. The FT process, developed by Franz Fischer and Hans Tropsch in 1923, was commercialized in Germany in 1936 and used during World War II. The NGNP Project developed a flowsheet (Gandrik, 2012) for the FT process in Aspen Plus. Multiple variations of the FT process have been developed for a wide variety of feedstocks, but all rely on the formula:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \quad (1)$$

where: n = a positive integer

The temperature and pressure maintained during the reaction, generally between 150 °C and 300 °C, and between 2 MPa and 3 MPa, control the specific product formula. Those values provide a reasonable match for downstream temperatures available with the HTGR's ROT.

4.4. Fischer-Tropsch and bio-mass to liquids model

RenTec was identified as a company that has completed a mid-sized biomass reformer demonstration. The RenTec reformer is unique in that the biomass and heated gas streams are separate, providing better reliability and supplemental power production. The RenTec gasifier produces synthetic gas and can be scaled, or smaller units can be operated in parallel.

The NGNP Aspen Plus model of the FT process was configured to couple the RenTec biomass reformer to the HTGR Intermediate Heat Exchanger (IHX) based on the parameters contained in RenTec's patent application (CLEARFUELS, 2011), as shown in Fig. 1. The red streams in Fig. 1 are the heated gas streams from the HGTR and match three of the heat exchangers shown in Fig. 3.

The RenTec-modified Aspen FT model was run to determine total output. It was determined that 10,000 barrels/day (bpd) of liquid fuels are produced from 366 MWt from the HTGR (converted to process heat