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Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle

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ABSTRACT

The high temperature nuclear reactor provides a new way to produce hydrogen with high efficiency. In the present work, the feasibility of using a VHTR for both electricity generation and hydrogen production is analyzed. The nuclear reactor is combined with a gas turbine, a steam turbine and a system for the delivery heat for high-, medium- and low-temperature processes. Industrial-scale hydrogen production via thermochemical water decomposition is considered, using high- and medium-temperature processes. Specifically, sulphur-iodine (S–I) and copper-chlorine (Cu–Cl) thermochemical cycles are examined. These water splitting cycles permit the conversion of water into hydrogen and oxygen at much lower temperatures than the direct thermal decomposition of water. Both cycles are considered promising routes for continuous, efficient, large-scale and environmentally benign hydrogen production without CO_2 emissions. The results show that the combination of a high temperature helium reactor, with a combined cycle for electric power generation and hydrogen production, may reach an efficiency of around 50%. The power plant cycle analyzed in the present paper is complex and it is difficult to determine conditions under which all target objectives are fulfilled: high thermodynamic efficiency for combined production of electricity and high-temperature heat which can be used to produce hydrogen.

Introduction

There are several nuclear reactor types in use nowadays around the world. Almost all are either of the PWR (pressurized water reactor) or the BWR (boiling water reactor) types. Most of the light water reactor power plants now operating are based on the pressurized-water reactor and they have relatively low thermal efficiencies. Similar to "conventional" coal-fired power plants, the nuclear units operate on a Rankine cycle but, for safety reasons, the temperature and pressure of the steam are much lower in the nuclear plant than in fossil

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fuel plants. As a consequence of lower steam parameters, especially temperature, typical thermal efficiencies of PWRs are about 33% and of BWRs are about 30% [9].

The efficiency of supercritical thermal power stations can reach 47–49% [33]. These plants are mostly fueled by coal and, for combined cycle gas and steam turbine plants, can achieve efficiencies of 58–60% [33]. Modern advanced thermal power plants may reach thermal efficiencies as high as 62% [6]. In spite of such achievements, such plants remain significant emitters of carbon dioxide. For this reason, reliable non–fossil fuel plant, such as nuclear power plants, are becoming increasingly attractive. However, current nuclear power plants have lower thermal efficiencies, with the best light water reactor power plant having a maximum efficiency of about 34–35%. A comparison of the steam pressure and temperature of current nuclear plants with the fossil-fuel plants shows that the thermodynamic efficiency of the current nuclear technology has not improved for many decades. Almost all current nuclear power plants, as well as the coming Generation III + plants, are not achieving thermal efficiencies as high as those for other advanced thermal power plants. The difference in thermal efficiencies between fossil-fuel plants and nuclear plants can be up to 30% [25].

One relatively straightforward option for increasing thermal efficiency involves raising the steam temperature with natural gas. In such a system, a thermal efficiency of around 40% is possible [9,33], which is similar to that for standard fossil-fueled power plants. Furthermore, for gas cooled reactors it is now possible to increase the reactor temperature from 850 °C to 950 °C due to technological advancements [6]. The modern gas cooled reactor is inherently safe, and thus can provide a stable and flexible option suitable for various energy supply applications. The development of such reactors is informative. First a continuous operation High Temperature Reactor (HTR) with an outlet temperature of 950 °C was successfully developed in 2010 [10]. By applying the existing technologies embodied in the HTGR and gas turbine, a nuclear power station was able to exceed a 50% thermal efficiency [29]. Typically, the high temperature gas reactor (HTGR) and the gas turbine modular helium reactor (GT-MHR) [2] refer to direct closed Brayton Cycle systems [17]. In the case of the very high temperature reactor (VHTR), the molten salt reactor (MSR) and the liquid fluoride thorium reactor (LFTR) [14], indirectly heated cycles are typically used. It has been shown that thorium, being four times more abundant in the earth's crust than uranium ores, is also a promising nuclear fuel. The liquid fluoride thorium reactor base plant, using high quality heat exchangers and turbomachinery with a 1200 K inlet temperature, can achieve a thermodynamic efficiency of 50 percent for electrical power generation [26].

The diversity of HTGR/VHTR power cycles is large [17,24]. Different power cycle configurations can be coupled to the same nuclear system depending on applications. This type of reactor is also a good candidate to produce hydrogen and its cycle configuration can vary depending on the technology to be used [13]. Recent studies on the thermal performance of such plants have been reported. In the HTGR regenerative cycle, the working fluid is helium and the thermal efficiency has been reported to be as high as 47.9% [34] identified the variables have the greatest influence on performance for each configuration and predicted efficiencies as high as 47.5% for the direct combined cycle layout. For a simple layout consisting of a two compression stages, a single stage turbine and a recuperator [23], determined optimum thermal efficiencies by parametrically varying temperature and pressure. The author found that the thermal efficiencies vary from 45% to nearly 52%, for a reactor outlet temperature of 850–1000 °C.

The results described above suggest that new Generation IV nuclear reactor plants should be considered fro implementation in the future, in large part because they appear to be capable of thermal efficiencies ranging from 40 to 50% if not higher. The high efficiencies are particularly advantageous because a low efficiency not only has a negative impact economically, but also environmentally due to extra thermal pollution. Therefore, future efforts to enhance nuclear power plant thermal efficiency appear to be merited.

Hydrogen energy can form an important element of energy policies for reducing carbon emissions. It can act as an energy carrier for transportation, fuel cells or as a commodity for the chemical industry. Hydrogen can be produced using off-peak electricity or continuously and stored for peak period use, e.g., in solid oxide fuel cells (SOFC). Hydrogen can be produced by several methods, including high-temperature electrolysis, steam reforming of natural gas, and high-temperature thermochemical processes.

At present, almost all hydrogen is produced by steam reforming of natural gas and from refinery streams. Each production process requires a large amount of thermal and/or electrical energy. The energy for this purpose can be produced in high or very high temperature nuclear reactors [11,22]. One of the most economical approaches for hydrogen production [4] using thermal energy are thermochemical cycles which use a series of chemical reactions and high temperature to convert water to hydrogen and oxygen. The maximum estimated theoretical efficiency for sulfur-iodine and copper–chlorine cycles is about 74%, but in practice, due to thermodynamic losses, these cycles exhibit similar overall thermal efficiencies, ranging from 37 to 54%. For conventional electrolysis, the overall thermal efficiency of hydrogen production can vary from 30% to 41% [35,36]. The cost for hydrogen production using thermochemical processes should be lower than for electrolysis because heat is converted directly to hydrogen, whereas electrolysis requires electricity produced with a thermal efficiency on the order of 40%. But it has been shown [21] that the overall efficiencies for hydrogen production using high temperature electrolysis can exceed 50% when reactor outlet temperatures are above 850 °C. Taking into account technical problems when introducing high temperature thermochemical processes having similar efficiencies, high temperature electrolysis also appears to be promising.

Of the various thermochemical processes, one of the leading candidates is the sulfur-iodine (S–I) process:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (\text{at } 120^\circ C) \tag{1}$$

$$2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2 \quad (\text{at } 850^\circ C) \tag{2}$$

$$2HI \rightarrow I_2 + H_2 \quad (\text{at } 450^\circ C) \tag{3}$$