Available online at www.sciencedirect.com

ScienceDirect

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

Adapting the zero-emission Graz Cycle for hydrogen combustion and investigation of its part load behavior

Wolfgang Sanz [a,*], Martin Braun [a], Herbert Jericha [a], Max F. Platzer [a,b]

[a] Institute for Thermal Turbomachinery and Machine Dynamics, Graz University of Technology, Graz, Austria
[b] AeroHydro Research & Technology Associates, Pebble Beach, CA, USA

ARTICLE INFO

Article history:
Received 12 September 2017
Received in revised form
9 January 2018
Accepted 26 January 2018
Available online 15 February 2018

Keywords:
Graz Cycle
Hydrogen combustion
Power generation
Part load behavior

ABSTRACT

A modern energy system based on renewable energy like wind and solar power inevitably needs a storage system to provide energy on demand. Hydrogen is a promising candidate for this task. For the re-conversion of the valuable fuel hydrogen to electricity a power plant of highest efficiency is needed.

In this work the Graz Cycle, a zero-emission power plant based on the oxy-fuel technology, is proposed for this role. The Graz Cycle originally burns fossil fuels with pure oxygen and offers efficiencies up to 65% due to the recompression of about half of the working fluid. The Graz Cycle is now adapted for hydrogen combustion with pure oxygen so that a working fluid of nearly pure steam is available. The changes in the thermodynamic layout are presented and discussed. The results show that the cycle is able to reach a net cycle efficiency based on LHV of 68.43% if the oxygen is supplied "freely" from hydrogen generation by electrolysis.

An additional parameter study shows the potential of the cycle for further improvements. The high efficiency of the Graz Cycle is also achieved by a close interaction of the components which makes part load operation more difficult. So in the second part of the paper strategies for part load operation are presented and investigated. The thermodynamic analysis predicts part load down to 30% of the base load at remarkably high efficiencies.

Introduction

In order to counteract the threatening climate change most countries regard it as virtually self-evident that they must concentrate on the development of the renewable energy resources within their national boundaries. However, there is a growing realization that the national resources are insufficient to achieve this objective. For example, MacKay [1] showed quite convincingly that the United Kingdom cannot replace fossil-based energy generation without recourse to nuclear power generation or without importation of energy from the outside.

Germany came to a similar conclusion and therefore proposed to take advantage of the elevated solar power densities in North Africa and the Middle East by building concentrated solar power plants there and transmitting the electric energy via high voltage direct current cables. The technical challenges

* Corresponding author.
E-mail addresses: wolfgang.sanz@tugraz.at (W. Sanz), platzer@redshift.com (M.F. Platzer).
https://doi.org/10.1016/j.ijhydene.2018.01.162

and the political instabilities in this region have impeded the implementation of this Desertec Initiative [2].

As an alternative in 2009 Platzer and Sarigul-Klijn [3] proposed a concept to exploit the global wind sources more easily. They suggest the use of sailing ships instead of stationary floating platforms so that the ships can be operated in areas of optimum wind conditions. In this concept the available wind power is converted into propulsive ship power which, in turn, is converted into electric power by means of ship-mounted hydropower generators. Hydrogen produced by electrolysis will be used for energy storage. In a number of papers Platzer et al. analyzed this concept in more detail, e.g. Refs. [4,5].

Due to the fluctuating nature of solar and wind power a storage system is also inevitable for land-based electricity generation from renewable energy in order to provide energy at the times of demand [6]. The limited storage potential of pumped hydroelectric storage, compressed air energy storage, flywheels and batteries, make Power-to-Gas (PtG) technology one promising option to overcome these limitations [7]. Surplus or intermittent power is used to produce hydrogen via water electrolysis. At demand, hydrogen can then be reconverted to electricity.

In order to find the optimum storage technology for electricity generated from renewable energy, in 2016 Walker et al. [8] compared Power-to-Gas with other energy storage technologies in applications ranging from residential load shifting to bulk energy storage and utility-scale frequency support. The authors found that Power-to-Gas is favorable for utility-scale energy storage where criteria such as energy portability, energy density and ability for seasonal storage are considered. PtG can provide significantly higher energy density than competing energy storage technologies. The ability of PtG for long-term storage of large amounts of energy led to studies of this concept for future renewable energy based systems in Great Britain [9], Germany [10] and Italy [11]. They showed that PtG is able to reduce the overall costs of the gas and electricity network and to improve system reliability in the case of large-scale use of renewable energy. E.g., in Great Britain electricity curtailment of 50–100 TWh in 2050 is possible without a large-scale storage technology.

Regarding electricity-to-electricity efficiency Walker et al. [8] showed that for bulk energy storage the storage efficiency of PtG is only about 35% at current technologies compared to pumped hydro with 82% and batteries ranging from 60 to 90% depending on the technology. But the batteries are far more expensive and do not have seasonal storage capability. In Ref. [12] a hybrid PtG-battery system was investigated with the result that batteries can support electrolyser operation but at too high costs.

So if hydrogen will be used as an energy storage system on a large scale, there is a need for highly efficient power plants for the re-conversion to electricity. In this sense Jericha et al. [13] proposed a hydrogen/oxygen fuelled steam power plant using fuel cells and gas turbine cycle components. The concept is based on the assumption that oxygen is provided "freely" together with hydrogen from the electrolysers. In their hybrid cycle about 20% of the net power output are generated by fuel cells, whereas the main output comes from the succeeding power plant. They predicted a net cycle efficiency of 74% which is far above the efficiency of state-of-the-art combined cycle power plants of 60%. In Ref. [14] Platzer et al. analyzed the energy conversion chain of the energy ship concept combined with the hybrid cycle and predicted that 44% of the hydro-turbine electrical power can be regained. Other researchers also proposed novel fuel cell/gas turbine hybrid cycles with the goal of highest efficiency. So Eveloy et al. [15] combined the hybrid cycle with an organic Rankine cycle, Wang et al. [16] proposed the combination with a Kalina cycle and Meng et al. [17] used an additional supercritical CO_2 process. The achieved efficiencies varied between 64 and 70%.

But the realization of the hybrid cycle concept lacks – besides the development work needed for the turbomachinery components – the availability of fuel cells of large power output. Therefore, in this work a concept is presented which also additionally uses the oxygen from the electrolysis for the hydrogen combustion thus leading to a power cycle of remarkably high efficiency without the need for fuel cells. In contrast to Ref. [6] where the hydrogen/oxygen combustion takes place in an internal combustion engine, a power cycle based on turbomachinery technology is proposed.

This cycle is more or less the Graz Cycle, an oxy-fuel cycle for CO_2 capture which has been developed at Graz University of Technology since 1995 [18]. Since then many further thermodynamic studies as well as component developments have been published, e.g. Refs. [19–22]. It is based on the internal combustion of fossil fuels with oxygen so that a working fluid consisting mainly of steam and CO_2 is generated thus allowing an easy CO_2 separation by condensation. Net efficiencies of more than 65% were predicted when the efforts for oxygen generation and CO_2 compression were not considered [22].

In this work the Graz Cycle is adapted for hydrogen/oxygen combustion so that a working fluid of nearly pure steam is available. This can be considered as a return to its origin, when Jericha firstly proposed a high-temperature steam cycle with internal combustion of hydrogen and stoichiometric oxygen [23]. A thermodynamic layout of the cycle is presented resulting in a power balance promising highest efficiency. Then a variation of important cycle parameters is performed to study the sensitivity of the plant to parameter changes. A final investigation of the part load behavior will prove the applicability of a Graz Cycle plant in a future energy system based on renewable energy and hydrogen as storage medium.

Thermodynamic layout

All thermodynamic simulations were performed using the commercial software IPSEpro v7 by SIMTECH Simulation Technology [24]. This software allows implementing user-defined fluid properties to simulate the real gas properties of the cycle medium as well as to add new models to the model library as the hydrogen combustion chamber. The physical properties of water and steam are calculated using the IAPWS_IF97 formulations.

Furthermore, a turbine module was developed for the calculation of cooled turbine stages. A simple stage-by-stage approach similar to Ref. [25] is assumed which allows calculating the amount of cooling steam needed per stage. The module assumes that half of the cooling mass flow is mixed to