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RENEWABLE POWER VIA ENERGY SHIP AND GRAZ CYCLE

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Abstract

The "energy ship" concept is briefly described comprising the use of large sailing ships equipped with hydro-turbines to generate the electric power needed to split sea water into hydrogen and oxygen which then are reconverted into electric power in shore-based hydrogen-oxygen power plants. An overview is presented of the current developmental status of the two rotating machinery components needed to implement this energy ship concept, namely hydro-turbines suitable for use on energy ships and compressors and turbines suitable for operation at the elevated temperatures required in the proposed hybrid hydrogen-oxygen power plants.

Introduction

Most countries regard it as virtually self-evident that they must concentrate on the development of the renewable energy resources within their national boundaries if they wish to convert to renewable energy generation. 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 and the political instabilities in this region have impeded the implementation of this Desertec Initiative [2].

In our view the time has come to regard planet Earth as a single spaceship whose air conditioning system shows signs of failing. The repair of this system therefore has to be regarded as a global problem that requires the mobilization of the global resources. Given the difficulties of converting the solar power directly into usable power, as evidenced in the Desertec Initiative, the question arises whether the global wind resources can be exploited more easily. Since the strongest and most persistent winds occur in certain ocean areas, especially near the Arctic and Antarctica, the question arises whether it is possible to exploit this vast ocean wind power reservoir.

The placement of large wind turbines on floating platforms in high-wind ocean areas poses great challenges, foremost among them the problem of hurricane survival. In 2009, Platzer and Sarigul-Klijn [3] proposed the use of sailing ships instead of stationary floating platforms so that the ships can be operated in areas of optimum wind conditions while retaining the ability to quickly move away from hurricanes. 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. For a given required power output the hydropower generators then are an order of magnitude smaller than the equivalent wind power generators as long as the ships can maintain a sufficiently high ship speed. Naturally, a large sail area is required to generate enough thrust to overcome the ship and power generator drag to maintain the required ship speed. In a number of papers Platzer et al [4, 5, 6, 7] analyzed this concept in more detail and showed that sailing ships with sail areas in the order of 10,000 to 20,000 m² sailing at speeds between 5 to 8 m/s in winds between 10 to 15 m/s can generate electric power outputs between 1 to 3 MW. This power then is used to split sea water into hydrogen and oxygen by means of electrolysis. The hydrogen gas is compressed and stored in tanks which then are transported in separate tankers to shore-based power plants for re-conversion into electric power or for other uses, such as heating, cooking or as transportation fuel.

It is evident that this energy ship concept [3] involves a significantly more complex sequence of operations than the direct conversion of wind power into electricity by means of large land or off-shore based wind turbines. Although more complex, there are three obvious benefits offered by this concept, namely access to a vast new wind resource, a higher capacity factor than achievable by land or off-shore based wind turbines, and production of storable energy in the form of hydrogen and oxygen. An additional welcome feature is the production of potable water as the power production “waste product”.

A further additional key technology for the exploitation of ocean surface winds is the efficient re-conversion of the stored pressurized hydrogen and oxygen into electricity. The Graz University of Technology in Austria has demonstrated the feasibility of operating industrial-scale hydrogen-oxygen power plants. Jericha et al [8] describe a hybrid power plant which incorporates solid oxide fuel cells into an innovative power cycle with steam as working fluid as described below. The total power output of this cycle is 139 MW at a net thermal efficiency of 74% where the hydrogen and oxygen are supplied from storage tanks at a pressure of 60 bar. This hybrid power plant therefore makes it possible to produce electric power at remarkably high efficiency.

It is the objective of this paper to provide an overview of the current development status of the rotating machinery components needed to implement the energy ship concept, namely hydro-turbines suitable for use on energy ships and compressors and turbines suitable for operation at the elevated temperatures required in the proposed hybrid hydrogen-oxygen power plant. For other details of the energy ship concept we refer to the cited papers.

Hydro-Turbines

The concept of dragging a turbine through the water is not new. At least two companies manufacture small turbines for the purpose of mounting them on sail boats to provide a small amount of on-board electric power for cell phone battery recharging etc.

We selected the UW hydro-turbine manufactured by AmpAir Energy Ltd in the United Kingdom for an investigation of its drag and power output. The turbine comprises a three-bladed rotor of 312 mm diameter (Fig. 1).

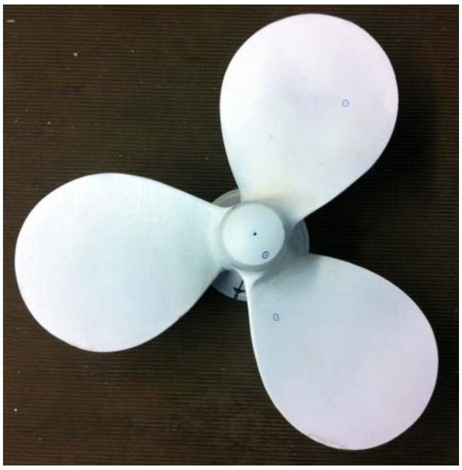

Fig.1 Test rotor.

For the computation of the drag coefficient the projected area of the three blades was used, amounting to 0.03645 m². The turbine was attached to a towing tank carriage using a 4.8 cm diameter aluminum pole, with a depth of approximately 20 cm. By removing the rotor from the complete turbine configuration, the drag of the generator alone could also be measured. The test set-up is shown in Fig. 2, where the generator is shown in blue, the rotor in grey and the sting in white. The tests were performed in the towing tank of the Naval Postgraduate School Hydrodynamics Laboratory and are described in detail by Bryan et al [9] and Bryan [10]. The measured power and drag values for various electric generator resistances shown in Fig. 3 are representative results obtained from these tests. The drag data points were taken at speeds between 0.68 m/s to 1.72 m/s. More details can be found in [9, 10]. They substantiate the power and drag assumptions made in [5, 7] to estimate the electric power which can be delivered by an energy ship with a given sail area and wind speed.

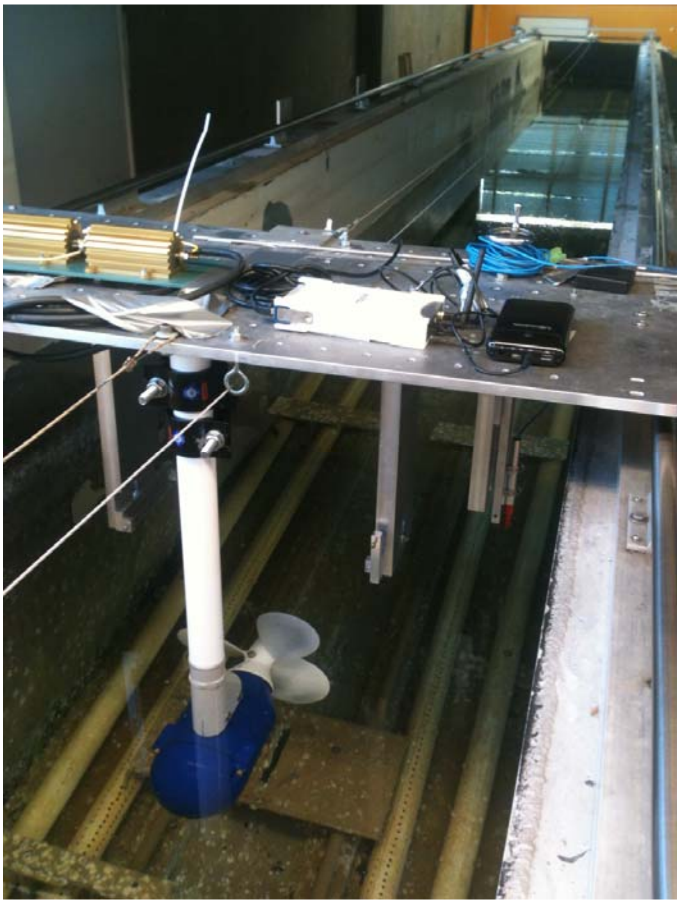

Fig.2 Test setup.

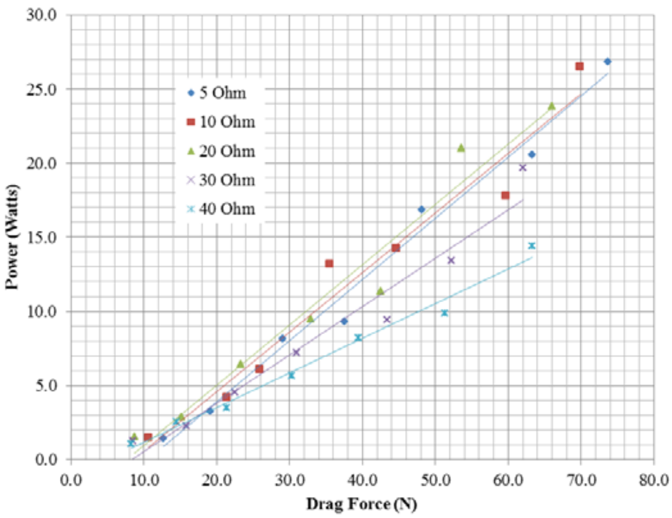

Fig.3 Measured power output versus drag for various electrically resistive loads resistances. [9]

Layout of Turbomachines for Hybrid Graz Cycle

Hybrid Graz Cycle Plant:

Before discussing the turbomachinery needed for the hybrid Graz Cycle of highest efficiency, the hydrogen-oxygen power cycle is described shortly. Jericha et al [8] propose a hybrid power plant which incorporates solid oxide fuel cells into an innovative power cycle with steam as working fluid. The power plant as shown in Fig. 4 is based on a previous proposal by Jericha [11] to use a high-temperature and a low-temperature cycle. The high-temperature part of the power plant consists of the fuel cells, the combustion chamber (CC), the high-temperature turbine (HTT), the high-pressure turbine (HPT), the compressor(C) and the heat recovery steam generator (HRSG). The low-temperature steam loop consists of the low-pressure steam turbine (LPT), the condenser, the feed pump, the deaerator and the steam supply to the steam compressor feeding the fuel cells. Steam is compressed to 41 bar and 600°C starting from 1 bar at 100°C, supplying the 12 fuel cells of 2.5 MWel which are arranged in parallel. Hydrogen and oxygen in stoichiometric ratio are fed into the fuel cells at 41 bar to deliver an electric output of 30 MW and to heat the steam to 800°C. Additional hydrogen and oxygen then are burned in a combustion chamber behind the fuel cells and the resulting 1550°C hot steam then is passed at 40 bar through the high-temperature turbine to produce an electric output of 123 MW.

At the outlet of the HTT we obtain steam at 1.1 bar and 670°C containing sufficient heat to feed a heat recovery steam generator producing high-pressure steam (190 bar) for the high pressure turbine HPT. After the HRSG about two-third of the 1 bar steam mass flow is sent to the compressor and further on to the fuel cells.

The HPT expands to 1.1 bar close to saturation delivering additional 23 MW electric output. The stream is then mixed with the remaining 1 bar steam coming from the HRSG and delivered to the low-pressure turbine of 14 MW electric output.

There the working steam expands to condensing conditions at 0.05 bar in the condenser (maximum wetness being 12 %). Condensate pump, deaerator and feed water pump follow conventional practice. After the condensate pump the combustion generated water is extracted to maintain the cycle mass balance. The feed pump compresses the water to 200 bar and delivers it to the HRSG. Some water

is led to the compressor inlet and outlet for quenching in order to obtain the optimal conditions at the fuel cell inlet.
The total turbine power is 160 MW, after deduction of the compressor and pump power a net generator output of 109 MW is delivered.
Together with the fuel cell power the total power output therefore is 139 MW at a net thermal efficiency of 74% for this hybrid power cycle.

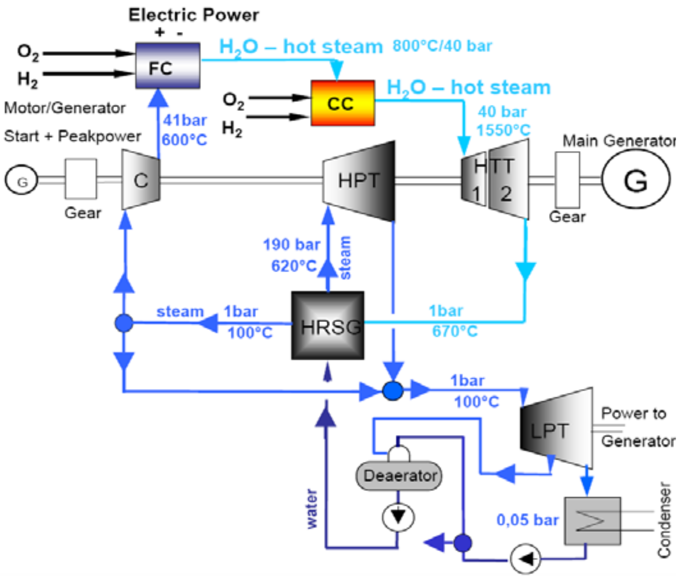

Fig.4 Principle and flow scheme of the hybrid Graz Cycle.

Turbomachinery Layout:
Since pure steam is used as working fluid some turbomachinery components of the hybrid power cycle cannot be considered as conventional and have to be newly developed. These are the steam compressor and the high temperature turbine. Steam compressors are mostly used for recovering lower pressure excess steam at higher pressure for reuse. But commercially available turbo compressors are not offered for the high pressure ratio of 40. Since the required technology is available the risk of development can be considered as low.
The situation is different for the high-temperature turbine. Although the operating conditions of 40 bar and 1550°C are state-of-the-art of current air-breathing gas turbine expanders, the unusual working fluid poses some problems. Especially the high enthalpy drop of steam leads to a larger number of stages and steam has to be used for blade cooling.
In order to show the feasibility of the hybrid Graz Cycle the layout of the turbomachinery components is discussed.
The HTT turbine (see Fig. 5) is designed as a two-shaft turbine with a fast-running compressor turbine and a slower-running power turbine. The compressor turbine consists of one transonic stage arranged on a very-high-speed shaft (22432 rpm) together with the steam compressor and the high pressure turbine HPT.
After the first stage HTT1 the following stages of the HTT2 power turbine are arranged on a somewhat slower shaft running with 9400 rpm. This speed leads to a reasonable stage number of five at bearable disk stresses at the same time. Fig. 5 shows the drawing of these five stages on a solid rotor design with blade lengths from 90 mm to 350 mm attached in fir-tree roots on small elongation disks on the rotor drum.
For the cooling of the HTT compressor turbine (HTT1) and power turbine (HTT2) either conventional film cooling using steam or the innovative cooling system ICS is suggested (see Fig. 6). It consists of hollow rotor blades with radial slits on the pressure side from which a supersonic flow of cooling medium adhering to the surface is created. These coherent films starting on the pressure side go in both directions. The first slit row releases cooling steam flowing in the same direction as the main flow, whereas the second slit row creates a film which flows also partly against the main flow around the leading edge and then all along the suction side to the trailing edge. This system was tested in several arrangements in cascade and turbine test facilities [12, 13] proving the feasibility and the cooling improvements of this novel design method [14].
As mentioned before, the compressor is arranged together with the first gas turbine stage HTT1 and the high pressure turbine HPT on a very high speed shaft (22432 rpm). This high rotational speed is necessary to achieve a reasonable enthalpy drop for the HTT1 and especially for the HPT despite their small dimensions as a result of the low volume flow. The rotational speed is also limited by the tip Mach number of the first axial stages of the compressor running at the same speed.

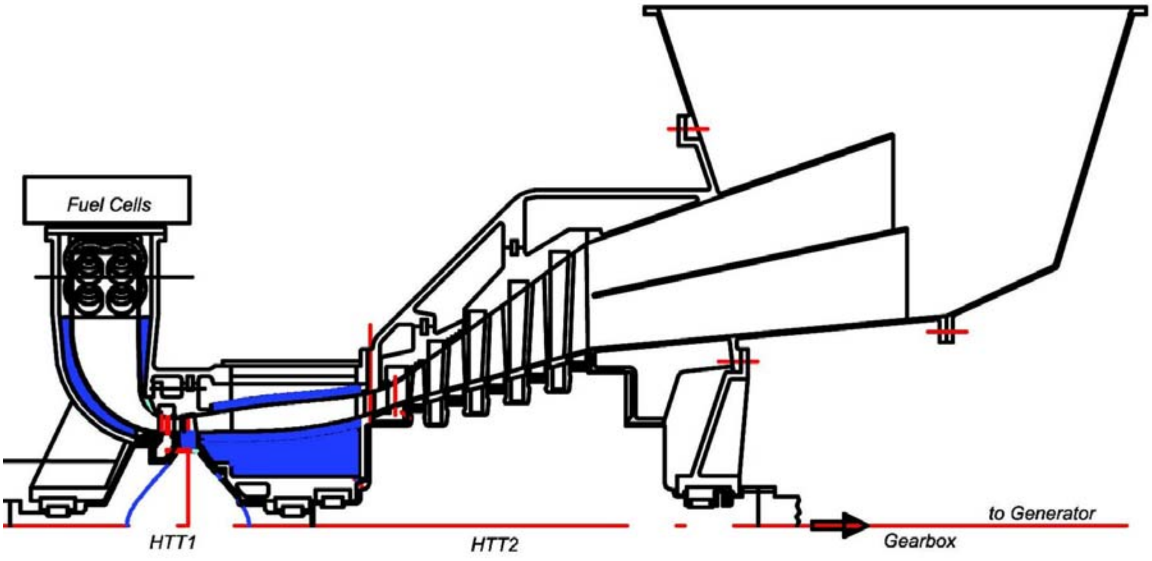

Fig.5 Design of the high temperature turbine HTT.

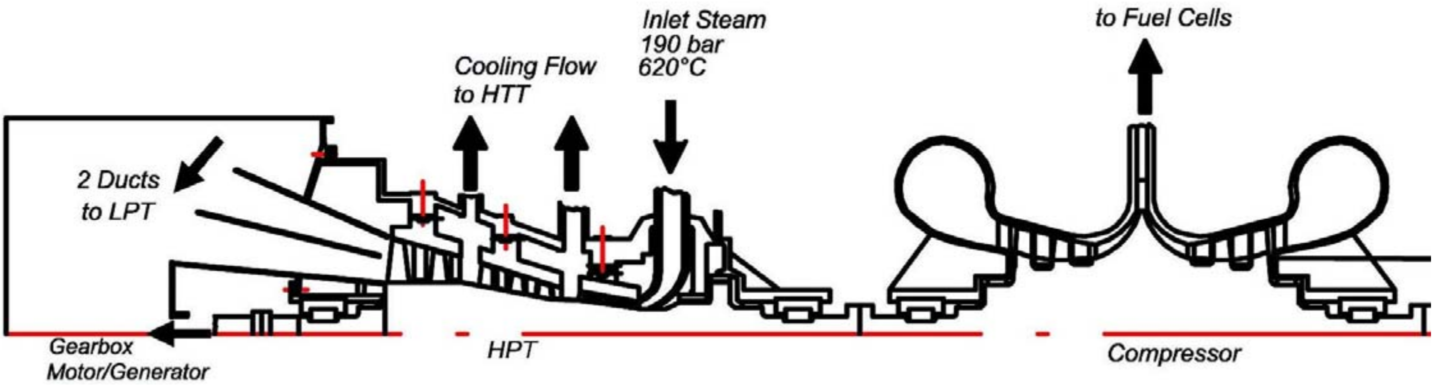

Fig.7 Design of the high pressure turbine HPT and the steam compressor.

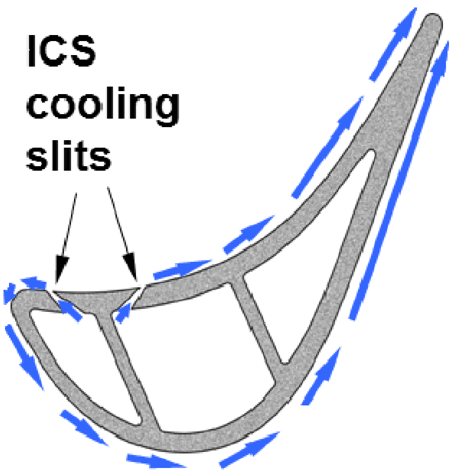

Fig.6 Cooing flow of innovative cooling system ICS.

The compressor design shown in Fig. 7 is envisaged as a double flow rotor with two axial stages on each side connected to a central radial disk. The disk is built in one piece together with the axial shaft parts which carry the above mentioned axial stages on both sides. So the general arrangement of the rotor is symmetric which allows inflow at low pressures from both sides and is creating an optimal flow situation in the radial diffuser leading the compressed working gas to the fuel cells. The axial stages contribute about half of the compressor pressure head. The first axial stages are checked for the admissible maximum tip Mach number of 1.4.

The HPT is running with the high speed shaft of 22432 rpm being directly coupled to compressor and first gas turbine stage (see Fig. 7). The inlet

pressure of 190 bar is high for the mass flow and the power output of this relatively small steam turbine. So high speed and a high number of stages are necessary. Steam is extracted in order to cool the high-temperature turbine (HTT1 and HTT2).
The design of the high pressure turbine HPT requires some further deliberations (see Fig. 7). Part load can be managed by lowering entry conditions, so that a control stage is not necessary. High efficiency is needed there, so that the design decision was made for a 50 % reaction blading and multiple stages at low rotor diameter. In a partly undivided casing rotor and attached blade carriers are axially mounted. In between the carriers taps are arranged to deliver cooling flow to the HTT. A balance piston is needed and is to be built in the usual way.
The power turbine is connected by a planetary gear to the main generator delivering the main power output. On the other side of the generator the low pressure steam turbine LPT is attached in the form of a conventional low-pressure three-stage turbine. The mean radius of the last stage is 1134 mm and the last blade length is 660 mm carrying conventional water droplet impingement protection (maximum wetness being 12 %). The speed is 3000 rpm, the turbine is contributing about 14 MW to the power output.

Overall Efficiency

In his study Stangl investigated the conversion rate of electricity produced by the hydro-turbine to electricity delivered by the hybrid Graz Cycle [15]. He considered a sailing ship large enough to drive a hydro-turbine of 1.5 MW power output. Osmosis of the salty sea water, electrolysis and compression of hydrogen and oxygen for storage consume about 41 % of the turbine power. If the hydrogen and oxygen are fired in a hybrid Graz Cycle, about 44 % of the hydro-turbine generated electrical power can be regained. Although the overall efficiency seems low compared to energy storage in hydro storage power plants, it has the advantage of access to vast new wind resources which could not be used elsewhere and higher capacity factors as described above.

Summary

The energy ship concept proposed and described in [3-7] comprises a number of technologies, ranging from large sailing ships equipped with modern rigid sails and hydro-turbines to sea water desalinators, electrolysers, hydrogen compressors and hydrogen-oxygen power plants. At first glance, this type of renewable energy production appears to be quite complex and inefficient. However, the analyses presented in [5, 7] show that the concept is quite competitive with onshore and offshore based wind turbines due to the much higher capacity factors and wind speeds available to energy ships cruising in high-wind ocean areas. Furthermore, the concept produces storable energy in the form of hydrogen.
Each of the above mentioned technologies is already relatively well developed; most development is expected for the high-temperature turbine of the hybrid Graz Cycle.
However, each technology certainly requires further development in order to optimize the concept. The above state-of-the-art review of hydro-turbines on sailing ships and turbines/compressors for the hybrid Graz cycle indicates the feasibility of their use for this type of renewable energy production.

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