The 4th International Symposium - Supercritical CO2 Power Cycles
September 9-10, 2014, Pittsburgh, Pennsylvania

THE EFFECT OF SUPERCRITICAL POWER CYCLES AT HYDROGEN PRODUCTION PLANTS

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ABSTRACT

Main He Hydrogen is an energy carrier rather than an energy source and as such it requires energy to be produced. It can be effectively used as fuel in in fuel cell systems, combining with oxygen to produce electricity and water.

Fuel cells and hydrogen are long-term energy technology options. They can make only a limited contribution to the 2020 EU targets on green-house gas emissions, renewable energy and energy efficiency, but definitely can help in meeting the goal of cutting greenhouse gas emissions.

One of the most promising technologies is connecting hydrogen production with high temperature He-cooled reactors.

Current structure of high temperature energy conversion is well established, using Brayton cycle with gas and optionally connected with steam cycle. Great effort is spent to reduce the energy consumption for hydrogen production, especially in terms of electricity. The way to achieve that is high temperature electrolysis, where preheating of the steam reduces electrical energy consumption in line with the decrease in Gibbs energy. The research and development of advanced solid oxide electrolytic cells (SOEC) is a key enabling technology.

The goal of this analysis is to optimize the architectures of power conversion cycles, whether it is the Brayton and steam cycles as well as a supercritical CO2 cycle. Comparison with the currently used architecture is described and shall lead to the support of the supercritical CO2 cycle. High temperature He reactor with different working temperatures is supposed as the heat source.

Different power conversion cycles are compared, from the basic Brayton cycle to the combined gas – steam cycle and the supercritical CO2 cycle. The key factors for optimization are also analyzed.

Several experimental devices were set up in UJV Rez, the newest device having the goal to experimentally verify high temperature hydrogen production with SOEC and maximum energy regeneration.

Hydrogen production

Hydrogen as an energy carrier for the transport and power supply industry is one of the most intensively studied topics nowadays. It is expected, world over, that there will be a gradual transition from the fossil-based economy (2000) to more ecological and source-independent hydrogen economy (2050). Related effort is performed on several levels – the topic is addressed at research institutes and industry and there is also a strong political support. The European Union has decided to become "a leading player" in a hydrogen and fuel cells field and consequently in 2008 founded Joint Technology Initiative for Fuel Cells and Hydrogen to support the necessary R&D.

Important reason for using hydrogen is an environment protection and sustainability. Transformation of hydrogen to electricity in a fuel cell is a very clean process, accompanied with water vapour as an only waste product. Hydrogen can be produced from a large number of raw materials (water, biomass, natural gas, etc.) using number of process energy sources including "home available" renewables, which minimises dependence on the strategic energy import. In the near future, nuclear energy will be probably one of the most important sources for hydrogen production due to the IV generation of reactors, which are very suitable, providing high efficiency.

Around 4% of the world's hydrogen is currently produced by conventional, low temperature, water electrolysis. An electric current is passed through the water causing it to dissociate into hydrogen and oxygen. Researchers have been investigating using solar energy and wind to power a conventional electrolyser to produce hydrogen (Glatzmaier and Blake, 1998). The efficiency of converting electricity to hydrogen in an electrolyser is as high as 80%, however, the efficiency of converting heat to electricity is less than 40%, yielding an overall efficiency of less than 35%.

High temperature electrolysis

High temperature electrolysis (HTE) is based on the technology of solid oxide fuel cells (SOFCs), which have been the subject of much R&D over the last 20 years. Whereas SOFCs consume hydrogen and oxygen to produce heat and electricity, solid oxide electrolytic cells (SOECs) consume electricity and steam and produce hydrogen and oxygen. Before entering the electrolysis cell, water is heated to form steam. The steam is supplied to the cathode side, where the application of a voltage breaks it down to give product hydrogen and oxygen ions. The oxygen ions migrate through the electrolyte to the anode where they give up electrons to form product oxygen. The voltage required is about 0.3 V lower than in conventional electrolysers due to the high operating temperature. In addition the kinetics are faster than at room temperature and so polarisation losses are avoided.

High temperature electrolysis of steam, at 800–1000°C, has several advantages over the low temperature alternative; the thermodynamic electric energy required is reduced, as shown in Fig. 1, and the activation barrier at the electrolyte surfaces is easier to overcome, resulting in an improved efficiency. However, significant problems exist in constructing stacks that have long lifetimes for the sophisticated catalysts required.

An electrolyzer is used for splitting of water into hydrogen and oxygen. Its function is based on reverse principle of Solid Oxide Fuel Cell (SOFC).

A yttrium stabilized zirconium oxide membrane has been introduced as a solid oxide electrolyte in the field of a solid oxide fuel cell and its applicability to a high temperature electrolysis to produce hydrogen was examined by the Japan Atomic Energy Research Institute. A high temperature electrolysis offers several advantages, such as (1) the amount of thermodynamic electric energy required could be reduced and (2) the electric current density would be increased due to a relaxation of the activation barriers at the electrolyte surfaces.

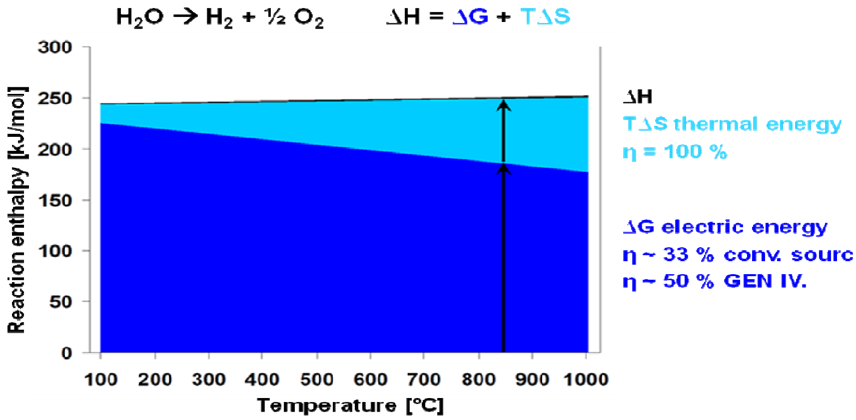

Figure 1. Energy balance of HTE

GFR 2400

The reference design for GFR (gas fast reactor) is based around a 2400 MWth reactor core contained within a steel pressure vessel. The core consists of an assembly of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fuelled pins contained within a ceramic hex-tube. The favoured material at the moment for the pin clad and hex-tubes is silicon carbide fibre-reinforced silicon carbide.

Figure 2 shows the reactor core located within its fabricated steel pressure vessel surrounded by main heat exchangers and decay heat removal loops.

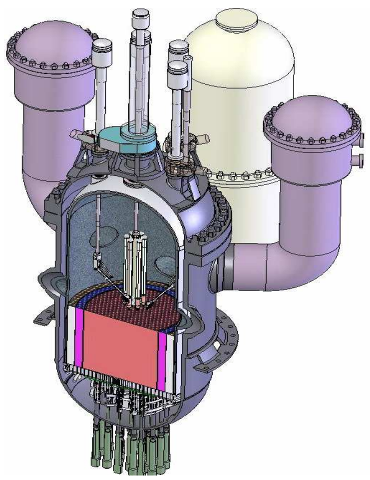

Figure 2. |View of GFR 2400 , core, cooling and DHR

The coolant is helium and the core outlet temperature will be of the order of 850°C. A heat exchanger transfers the heat from the primary helium coolant to a secondary gas cycle containing a helium-nitrogen mixture which, in turn drives a closed cycle gas turbine. The waste heat from the gas turbine exhaust is used to raise steam in a steam generator which is then used to drive a steam turbine. Such a combined cycle is common practice in natural gas-fired power plant and so represents an established technology, with the only difference in the GFR case being the use of a closed cycle gas-turbine. Fortunately, the use of an indirect cycle allows the working fluid for the turbine to be different from the reactor primary coolant. The introduction of nitrogen in the secondary coolant mixture reduces the technological risk and permits the gas turbine design to be much closer to that of established aero-derivative engines. Figure 3 shows a schematic of the power conversion system. Development of the core structural components, pressure boundary system and power conversion system are all considered to be fairly small evolutions from existing technology, although there are still some technical

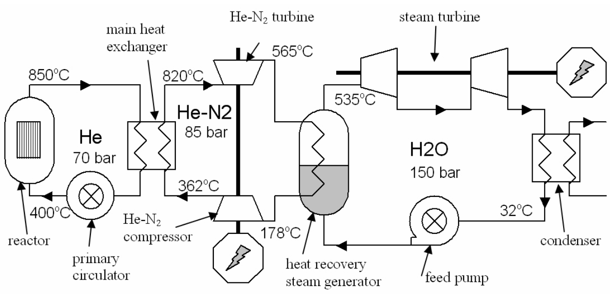

Figure 3. Power conversion sysrem of GFR 2400

Supercritical CO2 cycles with GFR

The supercritical power cycles are taking advantage of real gas behavior in order to achieve high thermal efficiency. The two most common supercritical cycles perform with water and carbon dioxide. The supercritical water cycle enhances thermal efficiency with rising turbine inlet temperature, while the supercritical carbon dioxide (S-CO2) cycle takes advantage of reduction of compressor input power (in comparison with classic Brayton cycle) due to changing properties close to the critical point (30.98°C, 7.38MPa).

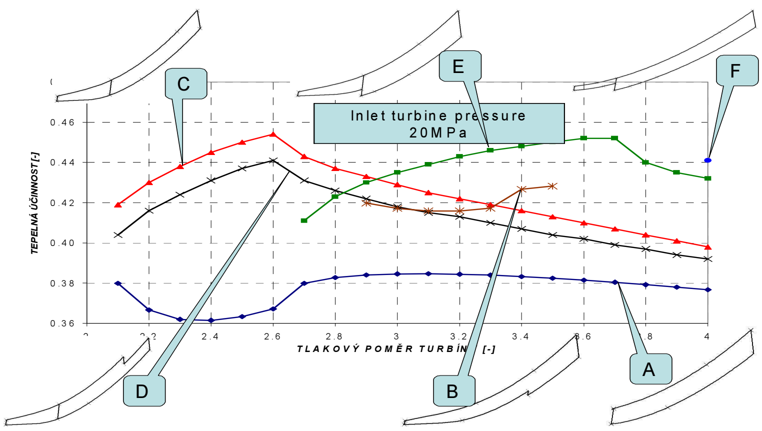

Figure 4. Different architectures of supercritical Co2 cyclesr

One of the main goals in the effort of development of new nuclear reactors is to raise the thermal efficiency. The supercritical power cycles are such candidates and are taking advantage of real gas behavior in order to achieve higher thermal efficiency. There are two main types of supercritical cycles, one uses water and the other carbon dioxide.

Great experience is available in the area of supercritical water cycles from classic fossil power energy, the power cycles with supercritical carbon dioxide are currently in the stage of development, calculations and testing. The main difference is given by the distant positions of the critical points of water and carbon dioxide. Generally speaking, the power cycle with CO2 shows very promising: the calculation with estimative values of components' efficiency gives high thermal efficiency, low capital costs, short period of construction, non-significant losses caused by corrosion as well as particularly small dimensions of turbo machinery.

The direct use of carbon dioxide cycles in nuclear energy is questionable as there is not sufficient world wide experience with this coolant. As a first approach, it seems that the optimal use of carbon dioxide cycles would be in combination with water, this solution shows the following advantages:

- high thermal efficiency of combined cycles;
- lower capital costs – lower pressure steam part is replaced by CO2;
- optimal thermal input for CO2 – condensation part of the steam cycle;
- fewer problems with erosion and corrosion – the low-pressure steam part is omitted.

Special aspects of hydrogen production with supercritical power cycles

The special issue for connection GFR with high temperature hydrogen electrolysis is to optimize the architecture and all parameters' of the cycle.

Main requirements' are not the same as in discussed GFR with gas and steam conversion. At GFR design as all suggested for maximum efficiency, for hydrogen production is necessary to receive also optimal cooling heat. The worst example is steam cycle at GFR, there is cooling heat at one very low temperature. approx. 40 °C. This heat cannot be used for water evaporation or other water heating.

From this view is situation with supercritical optimal. The cooling heat can be partially above 100 °C, so this heat can be used for high temperature electrolysis.

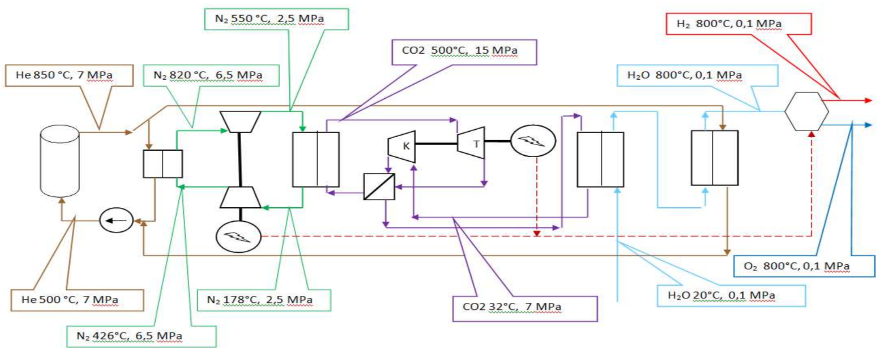

Figure 5. Architecture of supercritical Co2 cycles connected with HTEr

CONCLUSIONS

Is is not easy to find many factors supporting the goal to replace standard steam power conversion cycles with supercritical CO2. cycle. The calculated growth of efficiency about 2 – 3 percent is not factor exceeding the lack of experience.

But the comparison of waste heat is more important. At supercritical carbon dioxide cycle the waste (cooling) heat can exceed 120 °C , and that heat can be generally used, not only for the high temperature electrolysis.

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