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GRAZ CYCLE ENHANCEMENT BY MEDIUM AND HIGH TEMPERATURE FUEL CELLS

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Abstract

The Graz cycle - a well known gas turbine cycle proposal - designed for the optimal use of solar generated artificial fuels, shall be further improved in efficiency and output by the inclusion of fuel cells. A molten carbonate fuel cell MCFC, is envisaged for the methane oxygen fired version, whereas a solid oxide fuel cell SOFC will promote an innovative solution for the high temperature combustion chamber of the hydrogen oxygen fired version of the Graz cycle.

Introduction

The result of an intensive scientific discussion between Japanese partners from NEDO, CRIEPI and MHI has led to the conclusion, that the Graz cycle, already published in several versions, promises the best solution for the reuse of solar generated artificial fuels, in novel gas turbines of extremely high efficiency without any emissions to atmosphere. Thus a chemically and environmentally closed fuel cycle could be created between plants generating solar power and producing artificial fuels and those specific power plants which will be operated in the centres of electricity consumption. Thus avoiding any emissions or environmental problems.

As the reader can see from several publications, Graz cycle results have been discussed: Jericha, H., 1985; Jericha, H., 1987; Perz, E., 1988; Jericha, H., 1994; Jericha, H., 1989; Jericha, H., 1994; Jericha H., 1995.

Graz cyle H_2-O_2 version

The Graz cycle consists in the original version of a hydrogen oxygen fired high temperature gas turbine with connected low temperature Rankine cycle. The thermodynamic development process, having been proposed at the University of Technology Graz, Institute for Thermal Turbomachinery and Machine Dynamics (Prof. Herbert Jericha) was studied and fully endorsed by Mitsubishi Heavy Industries (MHI), which has led to common patent applications.

Following Carnot's principle, the heat input is effected at very high temperature, the highest imaginable in modern gas turbine technology, it is supported by a very modern cooling scheme, and since the reaction of hydrogen and oxygen leads to combustion water only, released in the combustion chamber in the form of high temperature steam, this cycle is completely a steam-water cycle. Thus it can be conducted with properly purified water, the cycle fluid whose thermodynamic properties are best known.

Three major components are under intensive development, in a co-operation, in which the University of Technology Graz and MHI apply modern gas turbine design philosophy, so that the development work in question is facilitated by the huge amount of research in power jets and stationary gas turbine technology.

The new components are, the steam compressor, which is required to recompress part of the expanded steam after cooling, from the exhaust of the high temperature gas turbine back into the combustion chamber, as an inert medium necessary to keep the maximum firing temperature at admissible limits. Here the translation from air flow, aerodynamic theory for aircraft compressors and stationary gas turbine compressors is well on the way, taking note of the different properties of the gases involved, i. e. air versus superheated steam.

The second turbo machinery component, is the high temperature part of the gas turbine which, due to the higher specific heat of steam (as compared to air or combustion products in air) is almost double, forcing the designer to double the number of stages to cover the same temperature drop, at the same time doubling the number of cooled stages with hollow blades. Here a novel cooling system is under consideration, which, by the use of high temperature steam will facilitate the realisation of this task.

The third component, which will be treated in detail here, is the high temperature combustion chamber. It effects a temperature rise of steam, from the range 500 to 700°C up to around 1300 to 1500 °C, at a pressure of around 50 bar, by the combustion of hydrogen and oxygen in special burners (Cimac 1991, Starzer). In order to obtain high combustion efficiency, these burners must serve for the complete reaction of both reaction partners i.e. hydrogen and oxygen. Any incomplete chemical reaction, would result in loss of one reaction partner and thus a reduction of combustion efficiency. So at the same time to avoid dissociation of the highly heated combustion products in the flame it is necessary to inject cooling steam immediately at the burners, within in the reaction zone.

So the property of the Graz cycle to provide high pressure steam of relatively low or medium temperature, opens up the possibility for proper cooling of burners and combustion chamber liner, as well as the cooling of the high temperature stages in the hydrogen gas turbine.

Improvement by SOFC

The improvement to be presented here, is the inclusion of an solid oxide fuel cell, into the combustion process of this high temperature combustion chamber. A solid oxide fuel cell works optimal in the temperature range of 900 to 1100 °C, so the inclusion of such a fuel cell into the combustion process, with a heat input of about 10% or maximum 20% of the total heat input to the combustion chamber offers the possibility for a staged combustion, which will certainly improve the combustion efficiency, as well as the required reduction of dissociation in the flame. So the solution in envisaged is the following way:

Staged combustion by catalytic reaction

A low temperature, more or less conventional gas turbine combustion chamber, of course using hydrogen and oxygen as fuel, and steam as cooling medium, will operate in the range of 500 °C or 700 °C up to 900 or 1100°C, then the SOFC will follow, with a further input of hydrogen and oxygen, as fuel for the SOFC, and the previously generated high temperature high pressure combustion product i.e. steam of 50 bar and 1000°C, would serve as the cooling medium for the SOFC. It would carry the losses of the SOFC with it, and of course it would carry the combustion product i.e. the combustion water generated and the surplus oxygen and hydrogen with it, further on to the third part of the combustion chamber. This part would be best designed as a catalytic combustion chamber, covering the range of 1100 to 1500°C by catalytic reaction on a ceramic surface, by further introduction of hydrogen and oxygen and generation of combustion steam into the process.

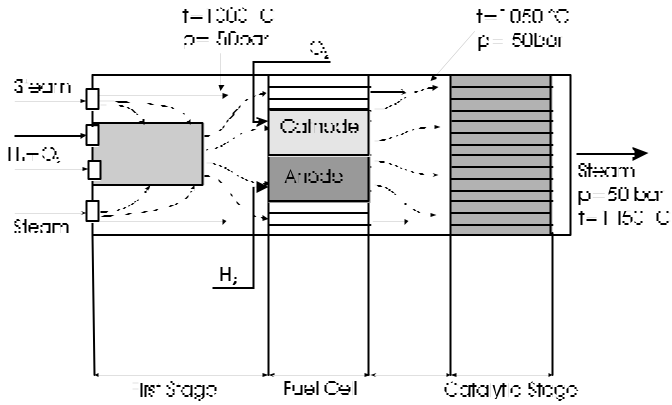

Fig. 1 Three stages combustion chamber.

Table 1 Power balance of the cycle, H_2/O_2 version

Turbomachinery	**Power [kW]**
High Temperature Turbine HTT	64 925
High Pressure Turbine HPT	4 270
Intermediate Pressure Turbine	1 455
Low Pressure Turbine LPT	7 995
Compressor	-15 108
Fuel cell	**5 200**
Power Output	**63 537**
-Feed Pumps	-193
Net Electrical Power Output	**68 544**
Heat Input (LHV)	92 693
Heat Input (HHV)	103 850
Thermal Efficiency (HHV)	**66 %**
evaluated to LHV	**74 %**

The improvement by the fuel cells results from the direct electricity production of the fuel cell at first hand, and secondly from the inclusion of the losses of the fuel cell into the Graz cycle, and the increased flow volume in the turbine by the additional fuel input, without further increase of maximum temperature, i.e. a larger flow volume through the gasturbine at the same maximum temperature at the inlet, since the combustion products from the fuel cell are expanded through the gas turbine.

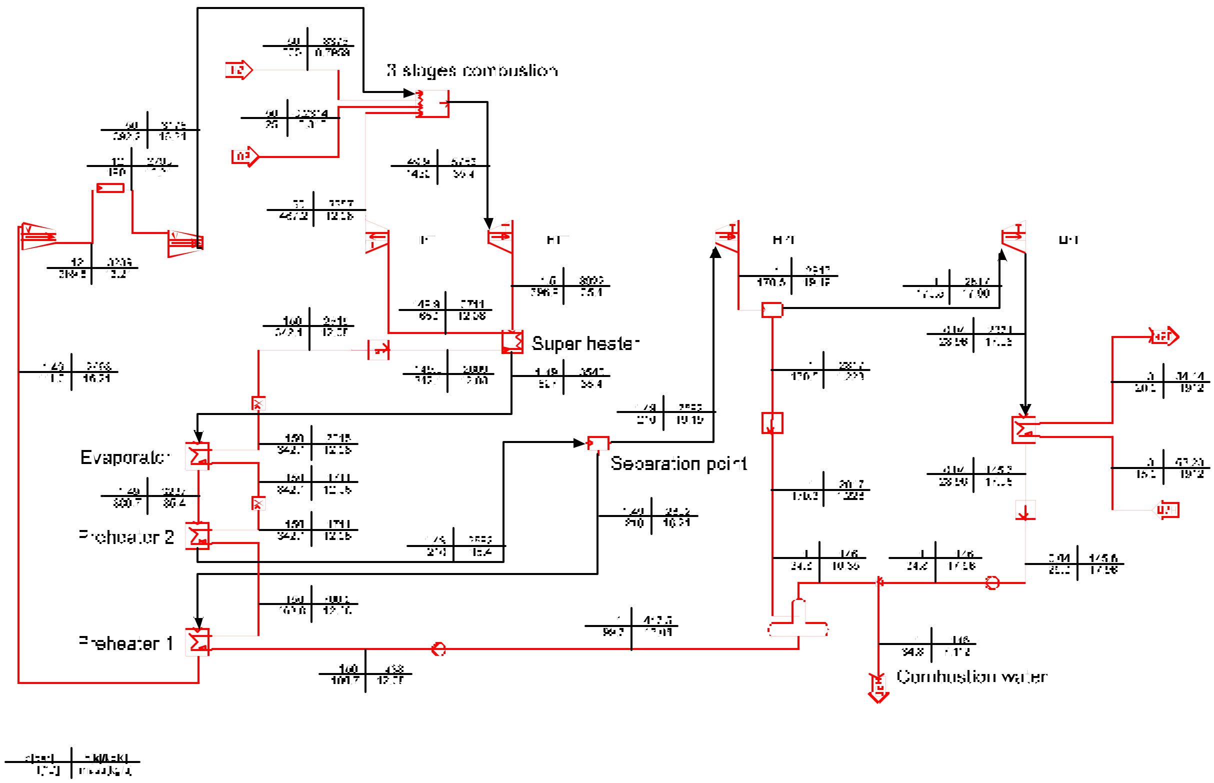

Fig. 2 Process scheme of the Graz cycle, H_2/O_2 version

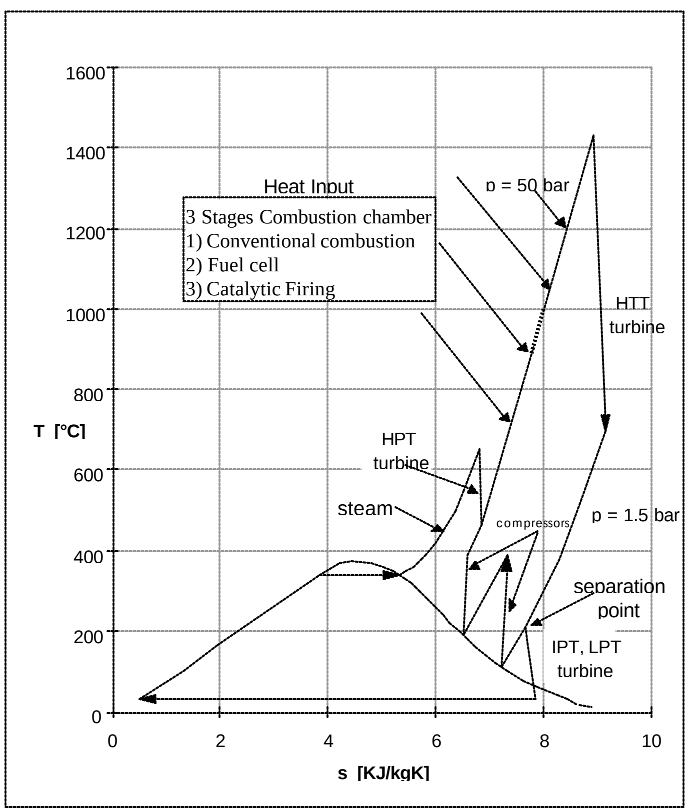

Fig. 3 T-s diagram of the cycle, H_2/O_2 version

Improvement by MCFC, Graz cycle methane oxygen fired version

This version has also been proposed by the University of Technology Graz, Institute of Thermal Turbo Machinery and Machine Dynamics, in several publications (Jericha, Cimac 1995; Jericha, ASME 1995). There were two reasons for this development, which can also be extended to the use of methanol as artificial fuel.

From German research results, and from the discussions with CRIEPI, NEDO and MHI, it could be concluded, that sea transport of liquid hydrogen would pose difficult problems. Liquifaction of hydrogen requires extremely low temperatures, and liquid hydrogen at the same time, is of relatively high specific volume, as compared to the standard liquefaction product LNG (Liquid natural gas). So oversea transport of liquefied hydrogen would be quite difficult.

Transport of methanol, would be as simple as any tank transport, and liquefied artificial methane could rely on the well proven LNG technology. So a fuel cycle could be envisaged, in which from the solar site to the centres of consumption artificial fuels, like artificial methane liquefied (LAG) or methanol would be transported, whereas in the power plants, in the centres of electricity consumption, i.e. large cities, the combustion products would be retained, i. e. the CO_2, and would be transported back to the solar site, where the artificial fuels would be chemically generated.

The problem of transport of oxygen has still to be resolved, it seems questionable wether it would be economic to transport liquefied oxygen as well, but in cases where pipeline connections to the solar sites are possible, it would be reasonable to transport the oxygen gained from the splitting of water and gained from the splitting of CO_2, together with the artificial methane to the power station in the centre of consumption. So, a solar energy system can be envisaged, which would operate completely within technical plants, without any load to the atmosphere, and so without any noxious or environmentally detrimentally emissions.

The second reason was, that in Europe, due to low solar insolation, solar power production would only be a very small alternative part of electric power. As a near term measure, for the reduction of emissions of CO_2, carbondioxide retention and storage in depleted wells or in deep sea, has been given some thought and quite some research work has been done in that respect.

Here it seems as well, that the Graz cycle can contribute a very valuable solution. In the methane oxygen fired version, methane is burned with oxygen, and the resulting CO_2 collected from the condenser, recompressed or even liquefied as required, and is made available at the system boundary, for storage or further use as part of the above mentioned solar energy system. The details of the cycle have already been published and discussed, and here the introduction of a fuel cell offers also interesting auspicies.

Molten carbonate fuel cell

Here would be an application for the already well developed MCFC, which is available in units of considerable power up to several MW, and which, in the specific proposal, where only a small part of the heat input is to be done by the fuel cell, a pilot plant of about 95 MW could be envisaged, where about 10 MW would have to be contributed by the MCFC. Here again, the losses of the fuel cell would be transported with the flow to the main combustion chambers burners, the heat loss and the combustion product as well, so that the fuel efficiency is raised to almost 100% of the MCFC, and the considerable contribution to efficiency and output is given to the Graz cycle thus enhanced.

In order to operate an MCFC, the splitting of methane, into hydrogen and CO is required, in order to have the fuel cell at optimum efficiency, the partial pressures of the reaction gases have to be high , so that the surplus of the gases has to be present at cathode and anode, a problem which can be solved in the case given, quite easily insofar, as a far larger amount of both reaction partners is available, and is brought to reaction in the gas turbine combustion chamber, so that these gases simply pass through the fuel cell anode and cathode, thus providing the necessary surplus and raised partial gas pressures. Again losses are carried on with these streams, and the combustion products carried on into the main combustion chamber, which is no disadvantage, since the reaction temperature of methane with oxygen is also very high, so that very high dissociation would take place in the combustion chamber flame, so that that it is necessary anyway to dilute both partners by inert gases, in the case given of the Graz cycle with steam, but also with the combustion products from both sides of the fuel cell.

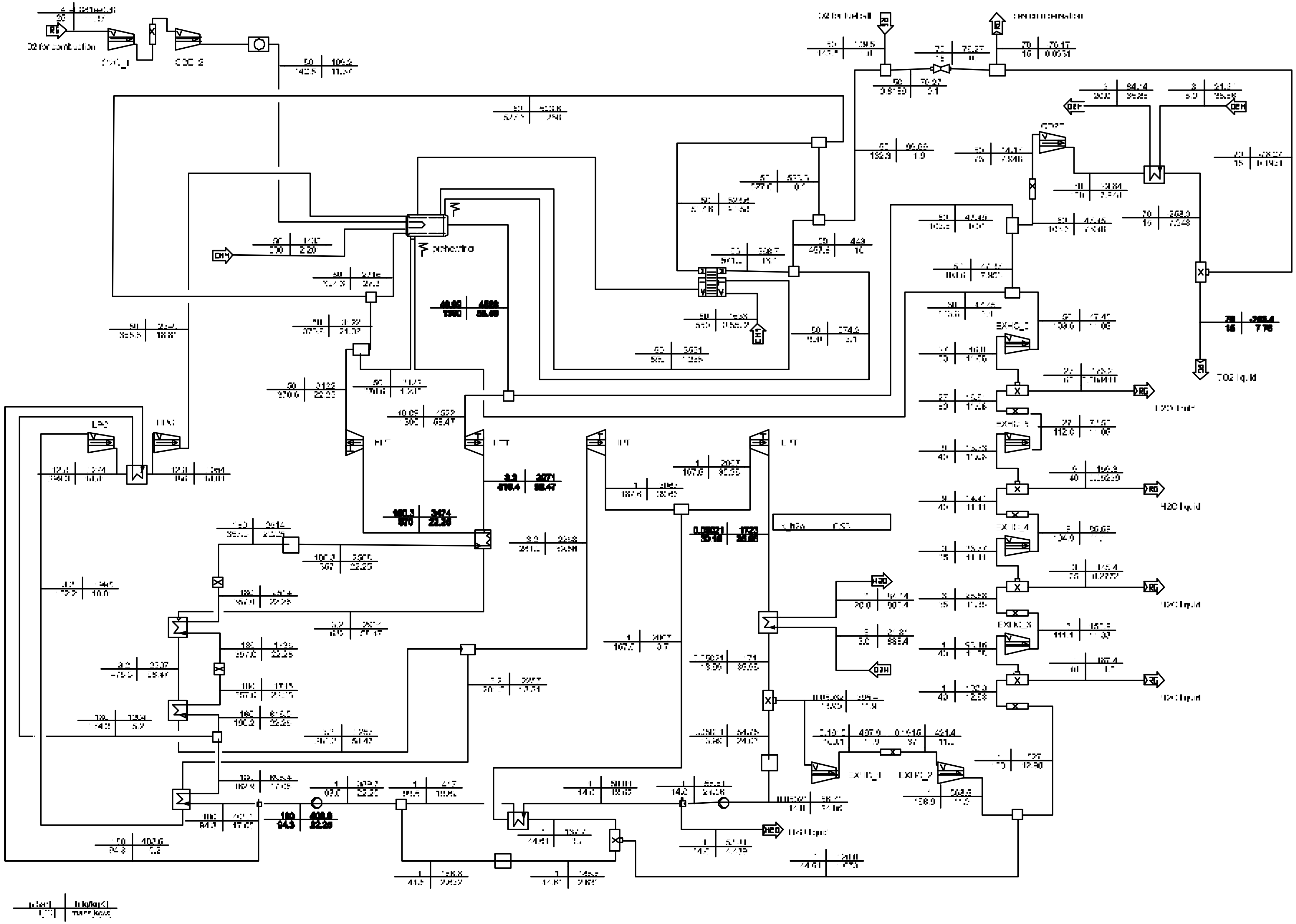

Fig. 4 Cycle scheme of Graz cycle, CH_4/O_2 version

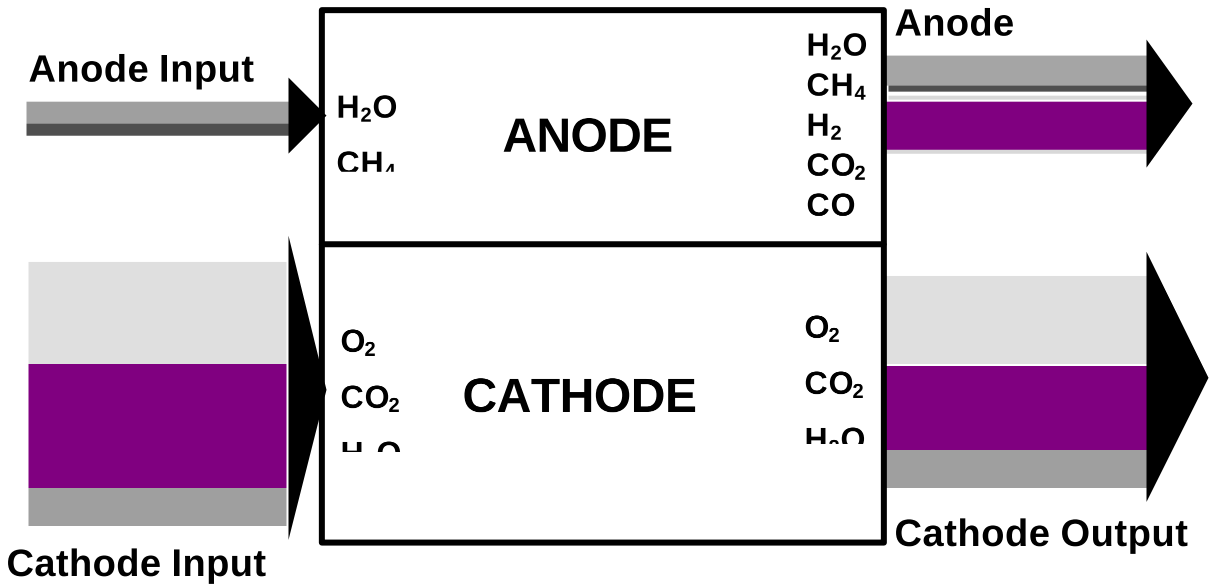

Fig.5 Reaction partners of the Internal Reforming MCFC (mass flow)

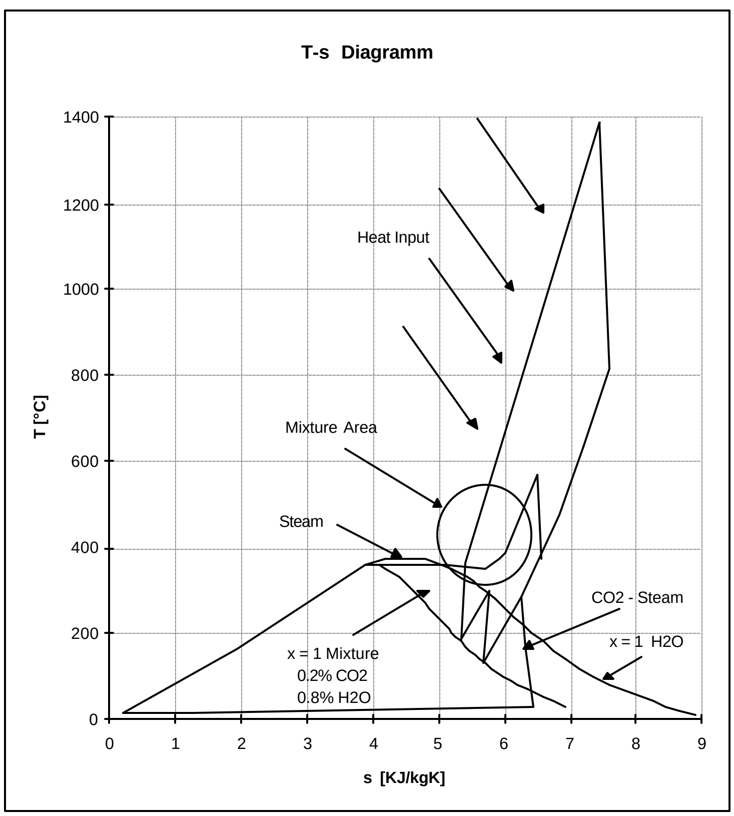

Fig. 6 T-s diagram of the cycle, CH_4/O_2 version

Table. 2 Power Balance of the CH_4/O_2 fired Graz cycle

	Power [kW]	Efficien. [%]
HEAT INPUT	**142,115**	
TURBINES		
HPT	7,815	90
HTT	73,146	91
IPT	7,549	90
LPT	12,362	90
Sum Turbine	**100,872**	
FUEL CELL	**10,000**	
COMPRESSOR		
LPC	5,244	86
HPC	5,559	86
EXH_1	1,220	86
EXH_2	1,693	86
EXH_3	209	95
EXH_4	189	95
EXH_5	182	95
EXH_6	95	95
Sum Compressor	**14,391**	
PUMP		
feedpump	429	98
condensate p.	2	98
Sum of Pump	**431**	
NET EL. POWER	**96,050**	
NET EL. EFFIC.		**67.6**

O_2 PRODUCTION FROM AIR	**Power** [kW]	**Efficien.** [%]
COMPRESSOR		
O_2C_1	1,571	95
O_2C_2	1,245	95
Sum Compressor	**2,816**	
O_2 PRODUCTION*	**17,059**	
NET EL. POWER	**76,172**	
NET EL. EFFICIEN.		**53.6**

1,500 [kWh/kg O_2]

CO_2 LIQUEFICATION	**Power** [kW]	**Efficien.** [%]
COMPRESSOR		
EXH_3	748	95
EXH_4	677	95
EXH_5	651	95
EXH_6	339	95
CO_2C	123	95
Sum Compressor	**2,538**	
NET EL. POWER	**74,311**	
NET EL. EFFICEN.		**52.3**
NET EL. EFFICEN. WITHOUT FUEL CELL		**50.1**

The net electric efficiency of the CH_4/O_2 fired Graz cycle of 67.6 % (LHV) is reduced to 53.6 % when the oxygen has to be produced from air and to 52.3 % when additionally CO_2 is liquefied for further use or storage.

Conclusion

The introduction of fuel cells in their proper temperature ranges, SOFC for the hydrogen oxygen fired version and MCFC for the methane oxygen fired version of the Graz cycle improves the efficiency considerable. Efficiencies of almost over 70% are reached. A noticeable increase in output for given turbo machinery size, and an improvement for the fuel cell operation, as well for the operation for the thermodynamic cycle itself, can be achieved. The properties of the high temperature Graz cycle, with the supply of high pressure cooling steam, facilitate the cooling of combustion chamber and high temperature gas turbine, and in the operation, in combination with a fuel cell, a further increase in efficiency and general effectiveness will make a solar energy system come up further upon the horizon.

Acknowledgment

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