Rapport SGC 191

An improved reactor system for small-scale fuel processing – the Optiformer concept

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Rapport SGC 191 • ISSN 1102-7371 • ISRN SGC-R--191-SE

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Summary

Catator AB (CAT) has evaluated a revised design of the previously described Ultraformer concept [1-3]. In comparison to the original Ultraformer, the new reformer concept (Optifomer) shows enhanced performances with respect to thermo-mechanic durability and conversion efficiencies. The unit is also easy to manufacture and ordinary high-temperature steel alloys may be used.

The new concept is based on a helix-shaped tubular heat-exchanger reactor designed by ICI Caldaie (ICI) fitted with CATs proprietary wire-mesh catalyst. The concept has currently been evaluated for production rates between 0.5 and 30 nm^3/hr of hydrogen and this report describes a detailed study of a unit for small-scale CHP-applications. Such systems will involve a fuel processor together with a suitable fuel cell, e.g. a solid-oxide fuel cell (SOFC) or a high-temperature PEFC (HT-PEFC) [4, 5].

The evaluations performed in this study indicate stable operation over a wide window of capacities with negligible emissions of hydrocarbons. Since it is possible to operate the re-designed unit at a higher temperature (>900°C) than the original Ultraformer unit (750-800°C), the conversion degree is much higher for thermo-dynamical reasons. The re-designed unit contains all necessary structures for vaporization, recuperation, effect supply and gas purification in a highly integrated structure. Furthermore, the unit is equipped with an internal insulation and a cooling jacked to reduce the skin temperature of the unit. The reactor has undergone about 100 full thermal cycles without any thermo-mechanical issues or catalyst degradation. Natural gas and different kerosene qualities have so far been evaluated with respect to conversion degree and possible slip of hydrocarbons. The conversion degree at rated load (100%) was above 99%, which enable us to reach superior efficiencies. If the unit were to be used together with a SOFC, the WGS-step could be omitted, reducing the size and weight further from about 2.2 l/kW_e and 3.2 kg/kW_e. In combination with a HT-PEFC, it is however recommended to reduce the CO-level to less than 2% for high-performance operation.

Totally integrated CHP-units have met a great interest in a variety of countries, e.g. in Denmark, Japan and Great Britain [6-8]. Such units are generally designed for an electricity output in the range 1-2 kW_e (close to the size reported in this study) and they may, depending on the market, operate on various fuels. In Europe, natural gas, biogas and LPG are the common fuel choices whereas Japanese CHP-programmes also are directed to kerosene.

CAT has previously shown that SOFCs are insensitive to small amounts of sulphur normally found in natural gas [9]. According to new studies performed by CAT under a contract with the Swedish Defence Material Administration (FMV), similar results have been observed for the HT-PEFC concept, which also has been reported elsewhere [10]. In addition, SOFCs are insensitive to CO whereas the HT-PEFC units can tolerate moderately high amounts without loss of performance [11]. The insensitivity of high-temperature fuel cells to various impurities makes it possible to build very simple systems, which can show a better reliability than complex systems involving extensive gas purification.

The next natural step would be to build a complete CHP-unit by combining the fuel processor with a high-temperature fuel cell. Such a project is proposed as an extension to the concluded study. Some conceptual information is given concerning a complete CHP-system based on a combination of the re-designed fuel processor and a HT-PEFC.

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1. Introduction

Catator (CAT) has previously designed, constructed and evaluated a compact fuel processor (Ultraformer) [1-3], see Figure 1. The unit is characterised by a high degree of integration in a compact structure. The unit can be run on a variety of fuels ranging from natural gas to heavy hydrocarbons under atmospheric conditions. The Ultraformer-unit consists of a number of unit reactors (catalytic burner, steam reforming reactor, water-gas shift reactor and PROX-reactor) tied together in a single-train unit. The fuel-processing unit is suited for combination with low-temperature PEFCs. Catator has also developed a novel reactor design for partial oxidation/autothermal reforming, which preferably can be combined with a solid oxide fuel cell, see Figure 2 below. This unit is characterized by its compact structure and its low weight (>1 kW_e/l, > kW_e/kg). It can be started in a few seconds and is simple and cheap in its design. The unit shown in Figure 2 below is fitted with internal insulation to reduce the skin temperature and the need for external insulation.

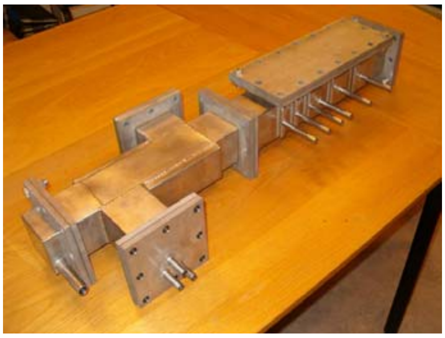

Figure 1 Picture of the Ultraformer unit for production of 3 nm^3/hr of hydrogen. The unit includes catalytic burner, steam reformer, WGS- and PROX-sections

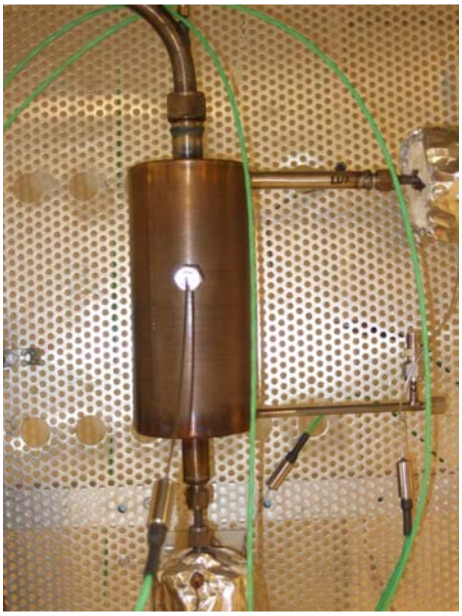

Figure 2 A Multiformer reactor for CPO/ATR

Depending on the design of the Ultraformer, the maximum operation temperature is limited to about 750-800°C, which means that the conversion degree is moderate for thermodynamic reasons. The structure is also somewhat sensitive to quick temperature changes. In order to improve the thermo-mechanic durability and to increase the conversion degree, the Ultrareformer concept was re-designed in a collaboration project between ICI Caldaie (ICI) and CAT, where CAT's wire-mesh catalyst was inserted into a coil structure designed by ICI. ICI is a leading boiler manufacturer located in Verona, Italy. The intention is to construct and sell fuel-cell systems for various applications, covering electric effect outputs from 1 kW_e to more than 30 kW_e. ICI have production skill and capacity for in-house mass manufacture of fuel processors and complete fuel-cell systems. They are also equipped with an advanced Hydrogen R & D lab to enable large-scale testing and lifetime validations.

By using a helix-shaped coil structure (EndEx-reactor), it is possible to avoid problems with stresses from thermal expansion and to increase the process temperature further, see Figure 2 below. The tubular concept might also be pressurized, which opens for systems involving gas purification by means of membrane filtration and pressure-swing adsorption. Similar units, based on heat-exchanger blocks, have previously been developed together with Intelligent Energy under a licence agreement [12]. Intelligent Energy also participated in a study performed by Catator aiming at utilizing said design in a Swedish refuelling project [13].

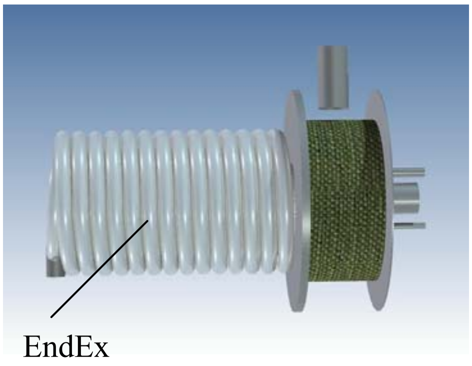

Figure 2 Helix-shaped EndEx reactor

The development work behind the unit evaluated in this study has focused on a number of problems associated with previous designs. First of all it is essential to use ordinary construction materials in order to converge to a realistic price level. Secondly, it of great importance to avoid thermo-mechanical issues often found in too rigid structures comprising stiff building blocks. Finally, it is important to provide a highly integrated unit comprising all balance-of plant components like heat exchangers, evaporators, re-cuperators etc in a compact and light-weight architecture. A cutting edge design must be described by three characteristics in general: low cost, high durability and top performance. Figures presented in the open literature let us believe that a reasonable target cost for a fuel cell system is around 600 Eur/kW_e once in mass production (approximately 1/3 of this figure is associated with fuel processing) so there is certainly no room for spectacular designs or exotic materials. The unit must enable trouble free operation for at least 20,000 hrs, preferably 40,000 hrs. It must also provide almost complete conversion of hydrocarbons during its lifetime (low degradation rate) in order to arrive at a high enough system efficiency.

The design presented in this study has been subjected to more than 100 full thermal cycles without any thermo-mechanical issues or catalyst degradation. The design is highly scalable, and coil-structures for hydrogen production capacities between 0.5 and 30 nm^3/hr have been tested in collaboration with our partners. This particular study focuses on smaller units, suitable for integration with fuel cells for CHP-applications. The size of CHP-units is typically between 1 and 2 kW in electricity and there are massive R&D-programmes running in a number of countries addressing such systems, e.g. in Denmark, Japan, Great Britain and in Italy. While gaseous fuels like natural gas and biogas are the main choices in Europe, Japanese companies also look on liquid fuels like kerosene. The unit described in this study has so far been tested with natural gas, methane (biogas) and kerosene containing different sulfur levels (<10 – 250 ppm, w). Future fuel choices may also include diesel, GTL-fuels (synthetic fuels), vegetable oils, glycerol and alcohols. Figure 4 below shows possible combination of fuel-processing systems, gas purification methods and fuel cells.

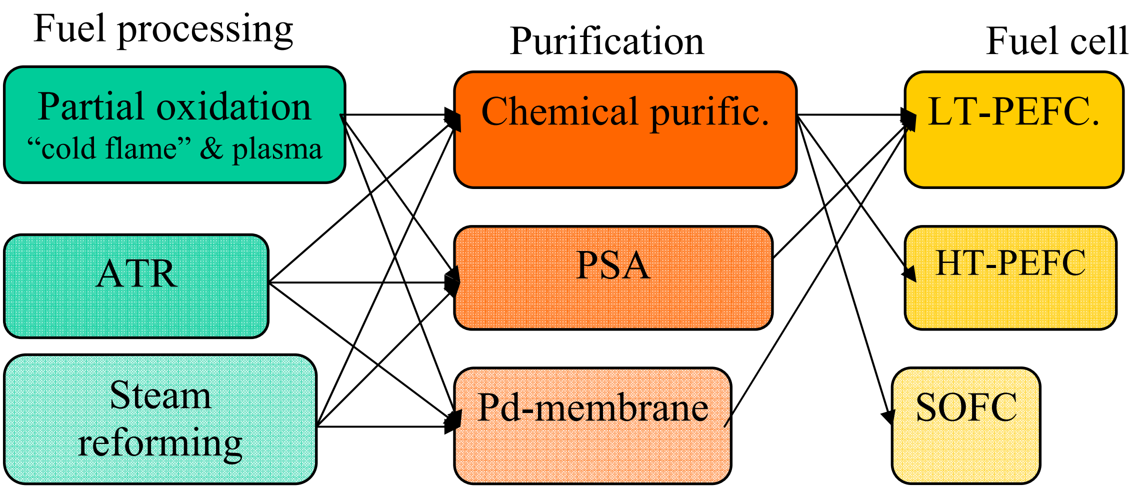

Figure 4 Small-scale electricity production in fuel cells is fungible.

Low-temperature PEFC are highly sensitive to CO as well as sulphur and an extensive reformate purification is essential for its function. Chemical purification (like in the Ultraformer unit) can provide acceptable reformate quality whereas physical purification (pressure-swing adsorption, PSA or membrane filtration) will provide essentially pure hydrogen. PSA and membrane purification can only be used in pressurized systems whereas chemical purification also can be used in atmospheric systems. HT-PEFC has a high CO-and S-tolerance and it is enough to include a simple chemical purification involving one shift step in most cases. In SOFCs, CO can be used as a fuel since the transport mechanism in the membrane involves oxide ions and not protons. The sulphur tolerance has also been shown to be quite high [9].

Since high-temperature fuel cells are rather insensitive to carbon monoxide and moderate concentrations of sulfur, such units can be directly integrated with the modified fuel processor to give a simple and compact CHP-unit. The drivers for massive implementation of small-scale CHP-units into the electricity grid are associated with increased efficiency and a higher flexibility on system level (less dependence on large power plants). In addition, small-scale CHP-units open up a diversified energy system where a variety of fuels might be used, renewable as well as fossil fuels.

2. Overarching aim and objectives

The overarching objective of the study is to demonstrate a unit with superior mechanical and technical characteristics as compared to the Ultraformer concept. The thermal integration is improved as well as the thermo-mechanic durability. The unit, as a whole, must also be easy and cost-effective to fabricate.

This study describes the evaluation and characteristics of a fuel-processing unit suitable for CHP-applications in Europe and Japan. The unit is possible to combine with either a solid-oxide fuel cell (SOFC) or a high-temperature PEFC (HT-PEFC) without extensive gas purification.

The study focuses on the design and on performance data obtained in experimental evaluations. Furthermore, the possibilities to combine the unit with fuels cells will be highlighted.

3. Problems observed in the Ultraformer design

The Ultraformer is built on a plate-type heat exchanger concept where wire-mesh catalyst is located between consecutive plates, which are welded together. The unit operates in counter-flow conditions for improved heat performance. Heat to power the reforming process is supplied by an externally manifolded burner equipped with secondary air supply to reduce the inlet temperature to the heat-exchanger reactor. Depending on the size of the heat-exchanger structure, the sensitivity to temperature phenomena might vary. Especially in very large units, it is essential to use rather mild operation conditions., i.e. longs start-up times. The reformate gas produced is then cooled in steps and enters a multiple step WGS-section with intermediate cooling. Finally, following more cooling, the gas enters a multiple PROX-unit comprising 3-4 separate PROX-steps. At the outlet, the CO-concentration is between 20 and 50 ppm (v).

As previously stated, the Ultraformer is suitable to combine with the highly sensitive low-temperature PEFC where the CO-levels preferably should be below 100 ppm (v). The Ultraformer cannot be operated as a pressurized unit, which means that reformate purification by means of Pd-membranes and PSA are not applicable. Depending on the manifolded burner and recuperators plus the absence of internal insulation, it is essential to provide excessive external insulation to arrive at a high overall efficiency.

Figure 5 shows the operation principle of the Ultraformer.

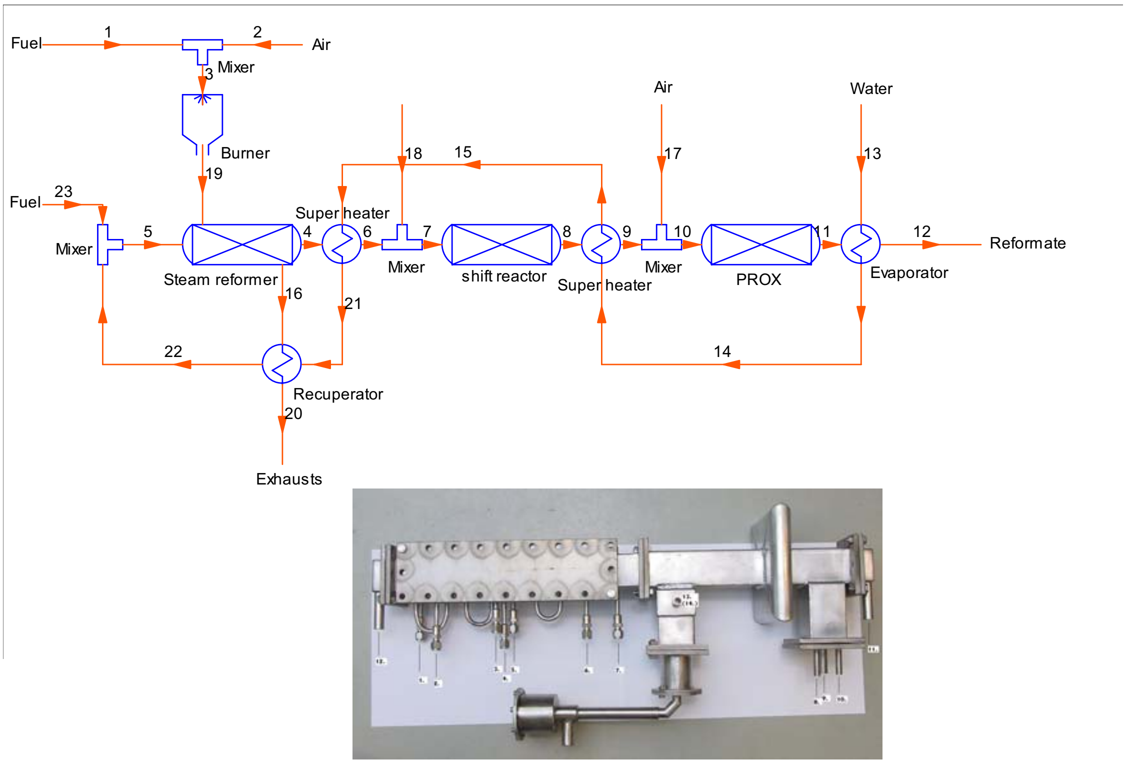

Figure 5 Operation principle, Ultraformer. CO-concentration in reformate typically less than 100 ppm (v). The picture shows an Ultraformer unit for liquid fuels.

The unit has been operated with a variety of fuels, both gaseous and liquid fuels. Most studies were performed on units ranging from 1 to 5 kW_e in capacity and with natural gas or alcohols as fuel. A number of tests have also been performed with heavier fuels like LPG, gasoline, kerosene and diesel. JetA1 has been tested in some military applications but the high sulfur content gave raise to poor performance with unconverted hydrocarbons in the reformate stream. In order to arrive at a high reformate quality with high sulfur levels, it is of importance to use high operation temperatures, clearly much higher than 750 – 800°C, normally used in this reactor concept.

The specific weight and volume of the Ultraformer is 0.3 kW_e/l and 0.1 kW_e/kg, which are values in the research frontline worldwide.

The main issues connected to the Ultraformer concept are associated with fabrication complexity, thermo-mechanic durability and the definite limits in operation temperatures. The current Ultraformer design contains a lot of welding work and a number of machined construction blocks. It also contains a series of cooling structure and multiple inlets for water and PROX-air. In order to converge towards the long-term cost target, it is essential to simplify the construction and to find a higher degree of integration.

In order to minimize the amount of catalyst, it would be of great interest to increase the operation temperature by 100 – 200°C. This is, however, not realistic in the Ultraformer design, depending on the thermo-mechanic sensitivity of the plate-type heat changers structure. If it were possible to find a flexible design capable of withstanding high temperature loads without mechanical problems, the performance could be enhanced greatly.

Consequently we need to present a fuel processor, which is simpler, cheaper and smarter than the Ultraformer concept. We have previously studied catalytically coated tubs (EndEx-tubes) in burner applications [14], with interesting and encouraging performance data. By inserting catalytically active coils or spiral catalysts into tubes and supplying external coating on the tubes by means of CATs proprietary technology, it is possible to produce tubular heat-exchanger reactors [14]. By winding this tubular structure into a helix, it is possible to produce a steam-reforming cartridge to be used together with one of CATs radial catalytic burners [15]. Some introductory experiments indicate that the catalyst utilization could be enhanced depending on a considerably higher operation temperature and that the effects of by-pass and uneven distribution could be totally omitted. Furthermore the, tubes might be pressurized, which might be interesting in refuelling stations were pure hydrogen should be supplied.

The EndEx-concept is a cost-effective approach to realize a highly integrated small-scale fuel processor with excellent performance. The next chapters will provide more input concerning the design of the unit and the performance as mapped in our experimental evaluations.

4. Measures to counteract the observed problems

The re-design work was in a sense split into two important areas:
- To find measures to overcome the temperature limits in the Ultraformer unit for improved performace
- To find a cheap fabrication method for the highly integrated unit

Generally speaking all types of mechanic constrains, will give raise to thermo-mechanic issues and the possibility of thermal fatigue and crack formation. The plate-type heat exchanger, used in the Ultraformer concept, is characterized by a highly constrained structure. During rapid heat-up (and emergency shutdowns) severe temperature gradients may occur within the structure. Consequently, the operation of the Ultraformer was subjected to definite limitations with respect to temperature raise rates, gradients and peak temperatures. By replacing the sheet metal structure with even more rigid structures (i.e. machined blocks), it is possible to improve the strength even if stresses will occur. If we also use highly graded metals, the strength can be improved further. The drawback is then that we obtain an extremely expensive, heavy and complicated unit.

CATs philosophy is instead to reduce the constraints and to allow for thermal movement and expansion. The ideal structure is the meander, constrained in only two locations and free to move in all other directions. The meander configuration could possibly be used but for fabrication simplicity we chose a helix structure instead. The double helix is constrained only at the top, giving room for free expansion axially and radially. Furthermore, this constrain is located in a position with low operating temperatures, i.e. the material strength is high.

The helix can be produced in one machining step from a rather standard high-temperature stable steel alloy and the catalyst coil can be inserted prior to the process or following the winding of the tube. External coating on the tube is supplied following the fabrication of the helix.

The dimensions of the helix are adapted to CATs catalytic burner technology. The catalytic burner is then placed in the centre of the helix. In this case we utilize CATs proprietary burner technology together with the previously developed coil-concept to provide a simple and durable core for a steam reformer. The dimension of the tube is normally around 12 mm (OD), but other dimensions might be used in smaller/larger units for practical reasons. The maximum diameter evaluated this far is OD 32 mm and the minimum is OD 6 mm.

By using internal insulation in the unit together with jacket cooling, the idea was to decrease the need for secondary insulation on the outside. The helix structure is also used for evaporation and superheating of the steam by harvesting heat from the burner exhausts. A detailed thermal analysis also indicated the possibility to integrate a WGS-step directly into the structure, based on catalyzed hardware.

The outlet temperature of the purified reformate will be close to the desired inlet temperature of a HT-PEFC, according to the thermal analysis.

The size and weight of the unit is around 0.5 kW_e/l and 0.3 kW_e/kg, i.e. somewhat higher than the corresponding values for the Ultraformer.

5. Design and integration possibilities

Catators proprietary catalyst technology and ICI´s heat exchanger assembly opens up for innovative catalytic process design. The Optifomer unit is an example of a highly integrated unit, where catalyzed hardware is used to combine catalytic and thermal processes. The core of the design is a catalytic tube structure shaped like a helix. Catator has previously developed computer codes to simulate said structures and Figure 6 shows the calculated capacity of the helix shaped tubes used in the Optiformer (tube diameter, 12 mm, length, 2 m). As can be seen in the Figure, the conversion degree becomes increasingly poor at capacities higher than about 2 nm^3/hr of hydrogen. The optimum area of operation is consequently up to about this value.

It is possible to obtain high mass-and heat transfer capacities without excessive problems with axial dispersion and slip. At very high loads, the pressure drop might be a problem, but it is then possible to use several coils in parallel without jeopardizing the efficiency. In very narrow tube it is possible to replace the spiral wire-mesh structure with a coil insert instead.

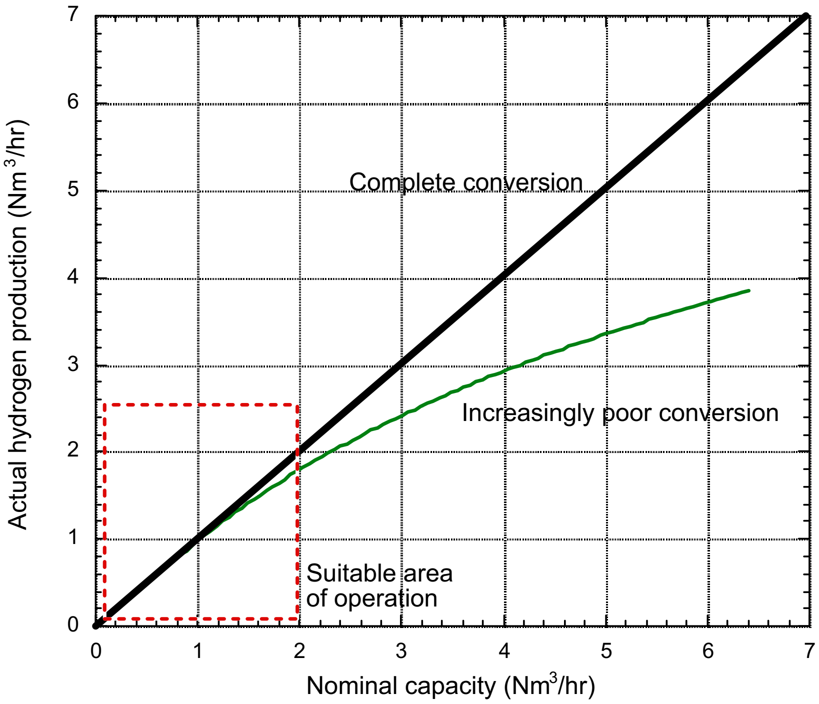

Figure 6 Capacity of the EndEx-configuration used in the Optiformer (d_i=10 mm, Length=2 m) versus nominal capacity.

Table 1 below gives suitable combinations of tube diameters, lengths and estimated capacities. The dimensioning work was based on 90 - 95% conversion of natural gas.

Table 1 Approximate tube dimensions for various capacities

Capacity (nm^3/hr of H_2)	Tube diameter (d_i, mm)	Tube length (m)
0.5 - 2	10	2
1.5 - 5	15	5
4 - 10	20	10
8 - 20	25	20
15 - 30	30	30

A schematic block diagram can be used to describe the process steps in the Optifomer unit as a whole, please refer to Figure 7.

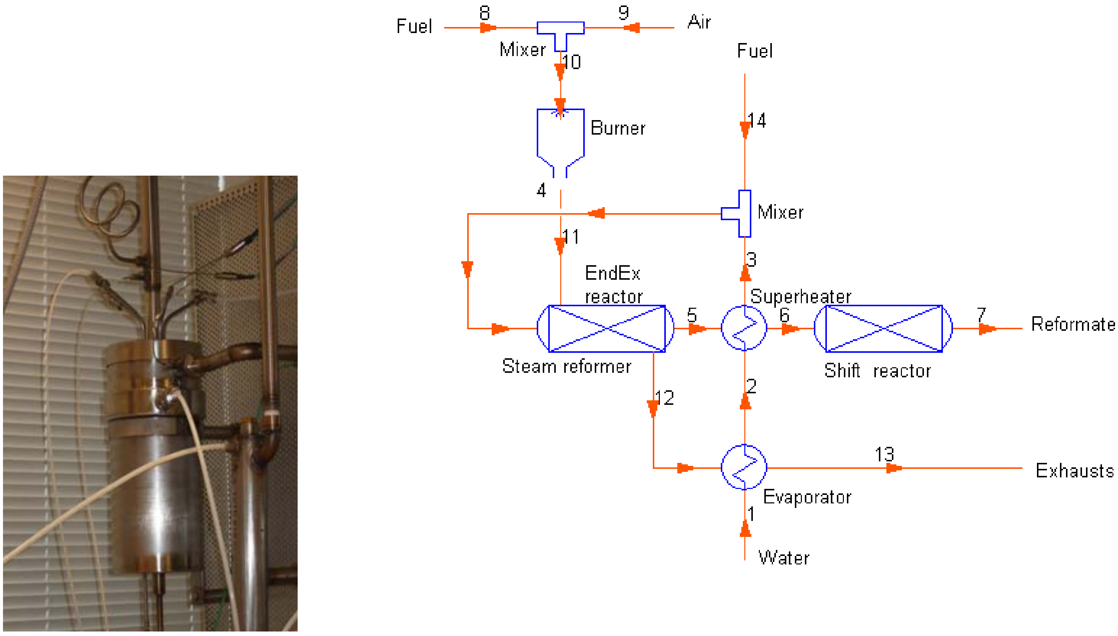

Figure 7 Process diagram showing the Optiformer concept

As indicated in Figure 7, the Optiformer is a highly integrated unit, comprising not only the steam reforming section and the burner but also all necessary structures for evaporation and super heating. In addition, it also contains and a water-gas shift section. The unit has an internal insulation and an outer cooling jacket. Despite that the operation temperature inside the unit is in excess of 1000°C, the skin temperature is limited to about 100°C. Hence, the need for additional external insulation is very limited.

The unit is powered by natural gas combustion in a radial catalytic burner. In tail-gas mode, the majority of the combustion is performed directly on the tubes assisted by the catalytic coating. Figure 8 shows a CFD-image of the heat transfer in two layers of coils. The hot combustion gas enters the first layer at about 1200°C and leaves at about 900°C. The second coil layer is used for pre-heating and pre reforming. The outlet temperature from the second layer is about 700°C and the remaining heat in the combustion gases are used for evaporation of water and preheating, as indicated in the block diagram above. The combustion gas leaves the steam reforming section at about 300ºC.

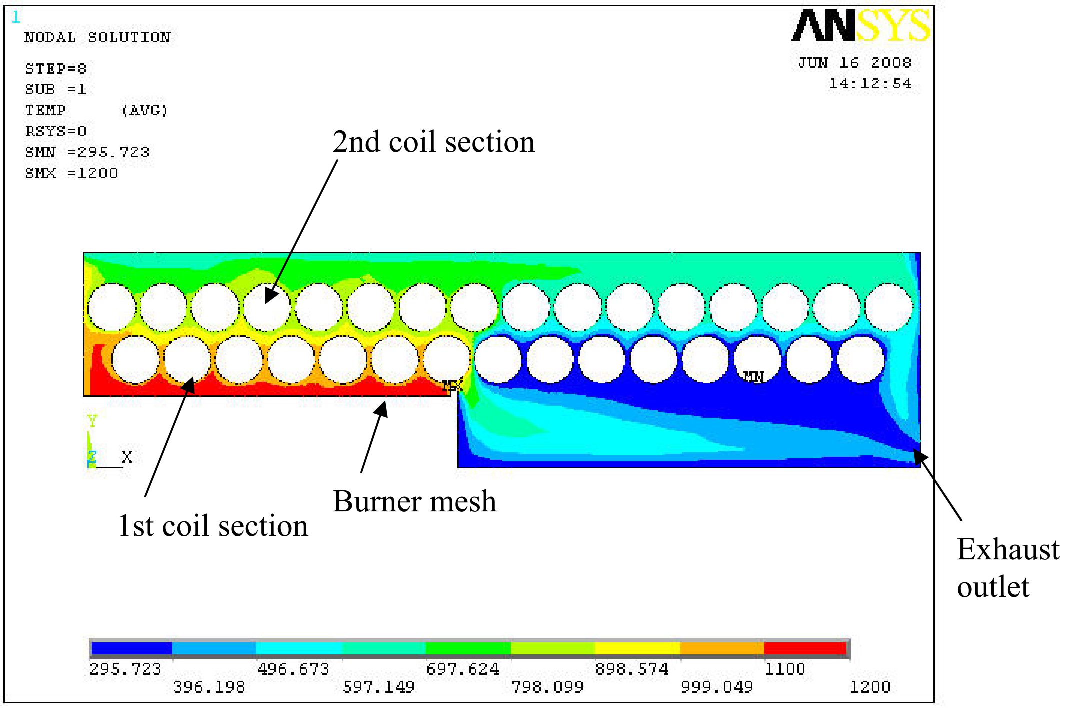

Figure 8 CFD-image of the coil section. 1st coil dimension, 53 mm (ID), 2nd coil dimension, 88 mm (OD), tube diameter, 12/10 mm (OD/ID). Exhaust flow rate 5 nm^3/hr @ 1200°C.

The idea is to combine the Optiformer unit with a high-temperature PEFC (HT-PEFC) to obtain a simple, compact and efficient system. Figure 9 shows a diagram of a total system based on the combination of an Optiformer unit and a HT-PEFC. As can be seen in the Figure, no sulphur removal is necessary in natural gas applications. The unit is designed to produce about 1.5 kW_e electricity and up to 20 kW thermal effect. The unit also contains a catalytic heat exchanger for heat production based on the Catator-SWEP concept, previously described elsewhere [15].

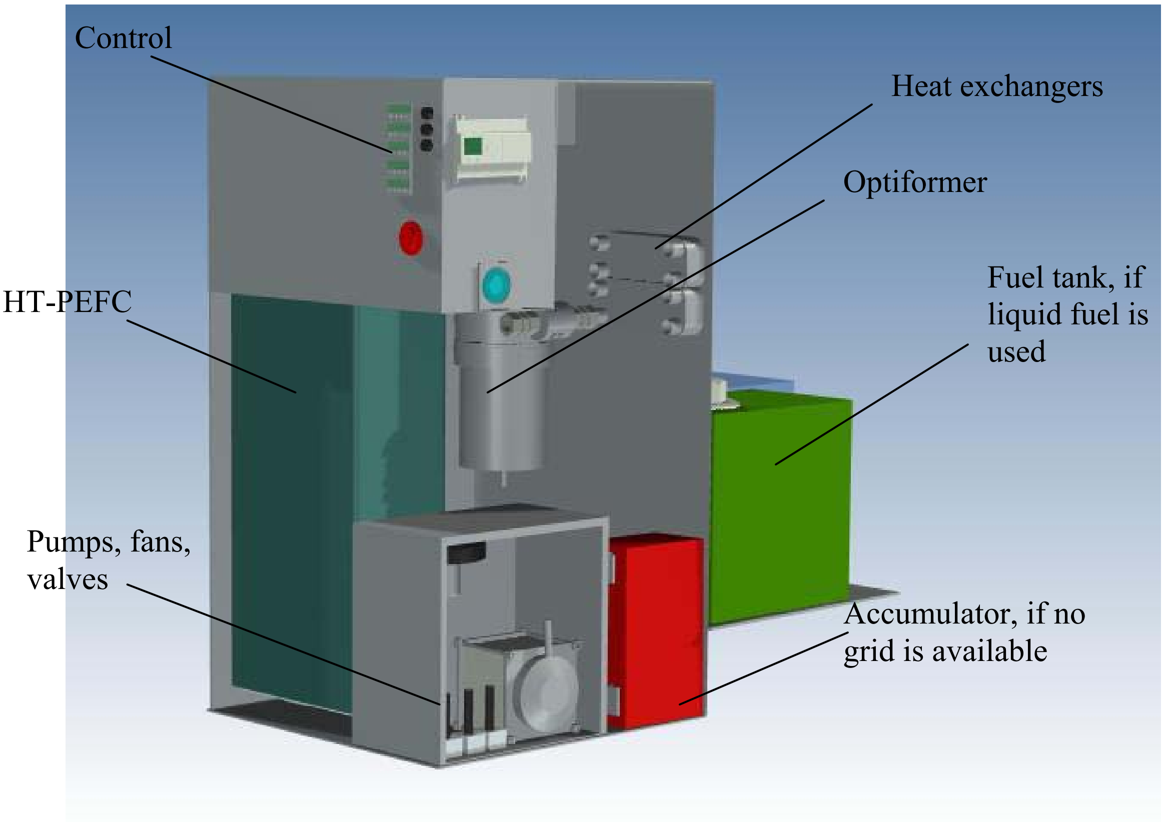

Figure 9 A CHP-unit, 1-2 kW_e + 20 kW thermal

6. Evaluation of a small-scale prototype

The Optiformer unit was installed in a specially designed rig for evaluation purposes. Fuel, air and water were supplied to the Optiformer unit. Tests were performed with natural gas and kerosene (environmental kerosene and jet kerosene containing sulphur and high concentrations of aromatic compounds). Analysis was performed with NDIR (CO, CO_2, HC), TCD (H_2) and GC-FID (HC). Thermo photos were taken in order reveal possible hot spots on the outside of the reactor during operation.

Figure 10a shows some performance data at a steam:carbon ratio of 3.5 – 4.5 when processing natural gas. Similar data obtained in the Ultraformer unit are shown in Figure 10b. The inlet temperature for fuel, water and air was about 20°C wheras the reformate outlet temperature was around 200°C, quite suitable for utilization in a HT-PEFC unit. The observed conversion degrees with respect to NG are in close agreement with calculated data (see Figure 6). At a production capacity of 1.5 nm^3/hr of hydrogen, the conversion degree was calculated to be 94% and we obtained 95% experimentally. Similar values at 0.8 nm^3/hr were 99.4 and 99.6% respectively.

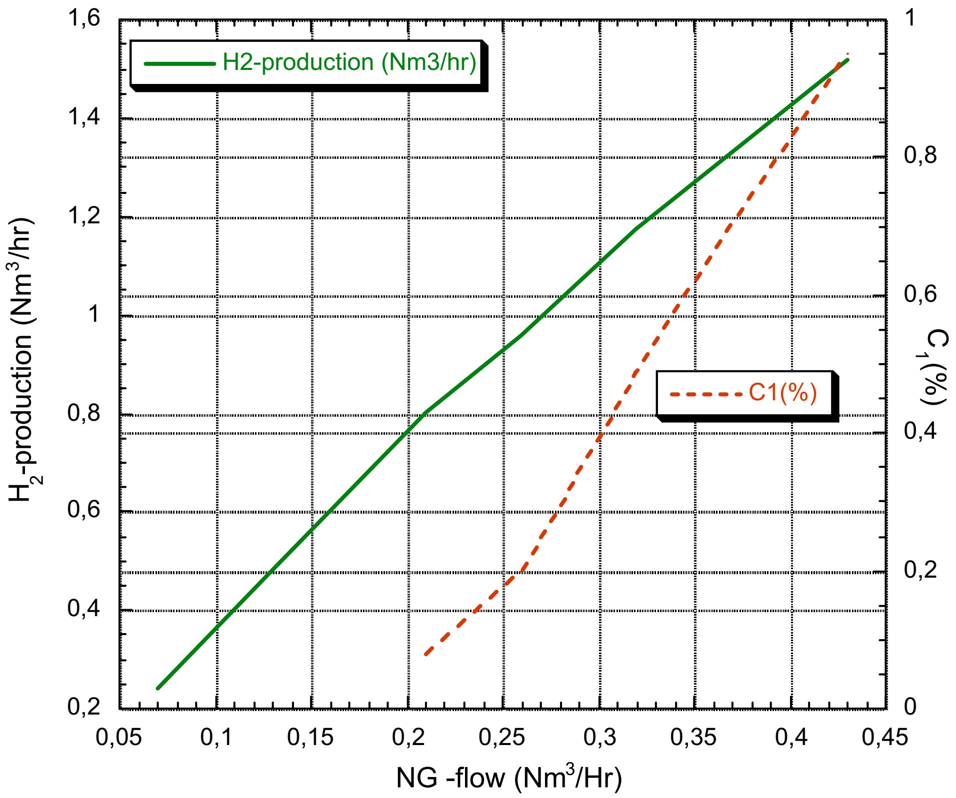

Figure 10a Hydrogen production and methane slip vs. capacity. Data obtained in the Optiformer unit

In its present configuration, the maximum capacity of the unit with acceptable conversion is around 2 nm^3/hr of hydrogen.

Detailed chemical analysis (GC-FID) indicates zero emissions (< 1ppm(v)) of heavier hydrocarbons normally found in natural gas. Indeed, methane is the most sluggish molecule to convert in the steam reforming unit.

The amount of catalyst in the Optiformer unit is only about 50% of the corresponding amount in the Ultraformer, which means that there would be a cost reduction also in the catalyst area.

If tubes with a large internal diameter (<20 mm ID) are used it is advisable also to include a helix shaped 2nd catalyst element in the centre of the tube to further improve the turbulence.

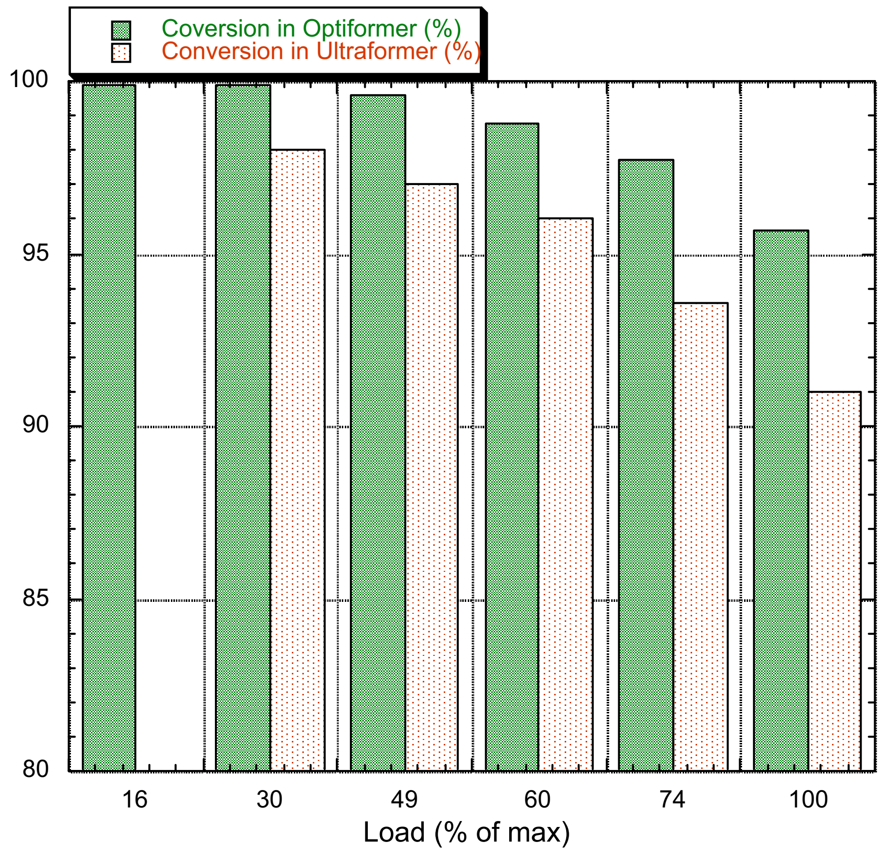

Figure 10b Comparison of Optiformer and Ultraformer with respect to conversion degrees

Indeed, it is obvious that the performance of the Optiformer is superior to the performance of the Ultraformer with respect to conversion degrees, especially at high loads. This observation is explained by the fact that much higher reformer temperatures can be used in the Optiformer without any thermo-mechanic issues. In the Ultraformer unit the operation temperature was limited to 750 – 800°C. Also, it was more difficult to achieve a totally uniform temperature distribution within the Ultraformer and some slip may have occurred.

Data obtained in steam reforming of kerosene are shown in Figure 11. Exactly as in the case with NG-processing, we obtain very high conversion degrees. Apart from minor amounts of aromatic compounds, it was also possible to process jet fuel containing up to 250 ppm (w) of sulfur.

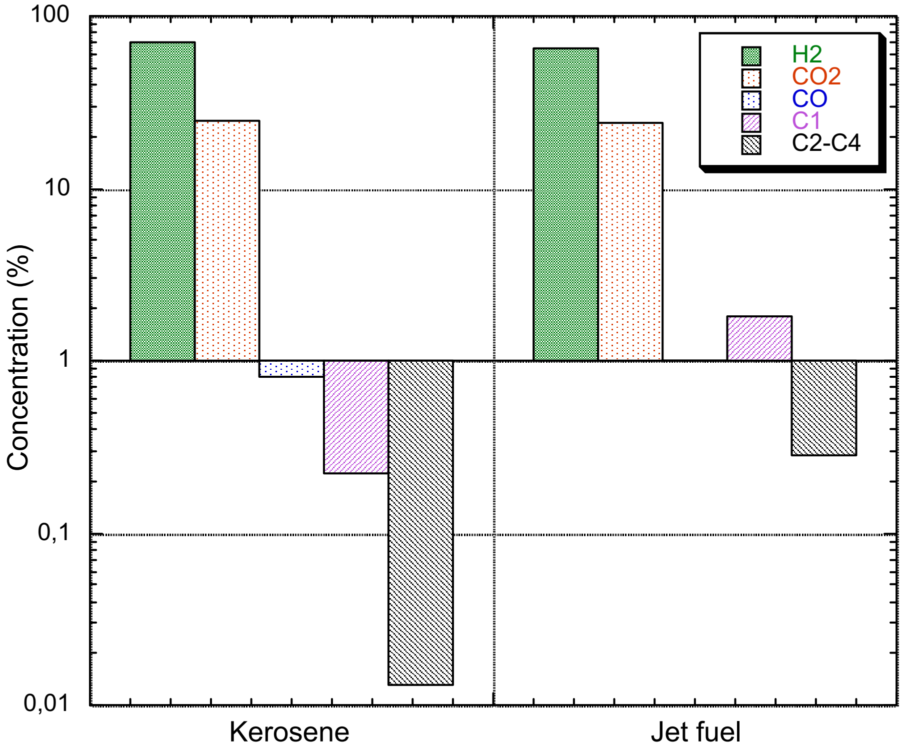

Figure 11 Steam reforming of kerosene. Comparison of low-sulfur kerosene and jet fuel (jet A1) with respect to slip of heavy hydrocarbons.

The maximum skin temperature of the unit was around 120°C, as can be seen in the thermo photo (Figure 12). This is a great step forward in comparison to the Ultraformer unit, which had no internal insulation. As a practical consequence, it is possible to limit the amount of external insulation on the Optiformer unit.

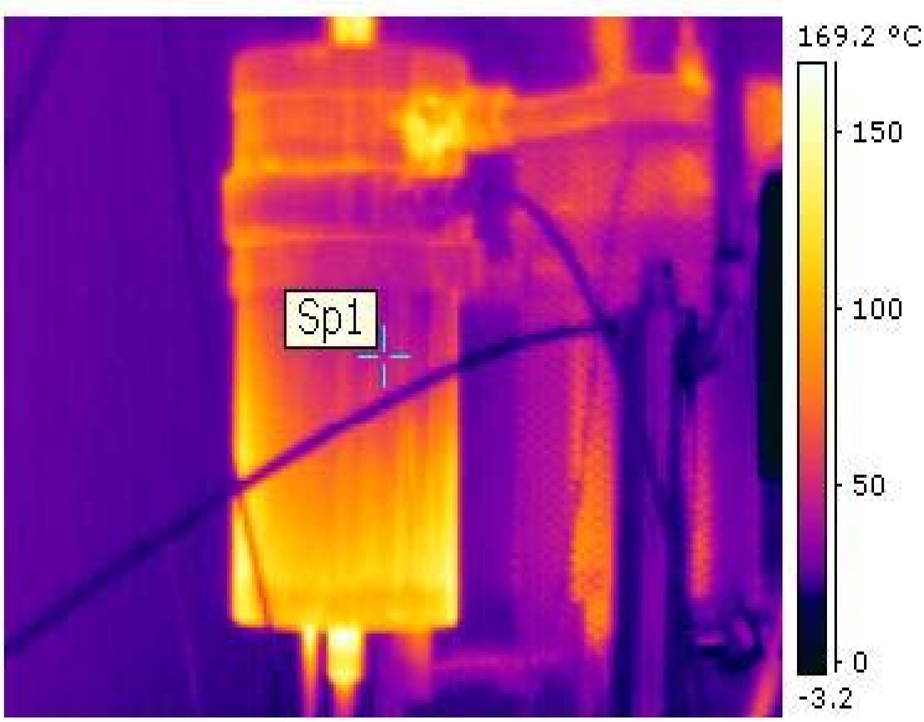

Figure 12 Surface temperature on the outside of the Optiformer during full-load operation.

The thermal efficiency of the Optiformer, if it were used in a fuel-cell system is well above 80%, see process scheme in Figure 13. By utilizing the anode-waste gas on the burner side it is possible to optimize the whole system with respect to energy losses.

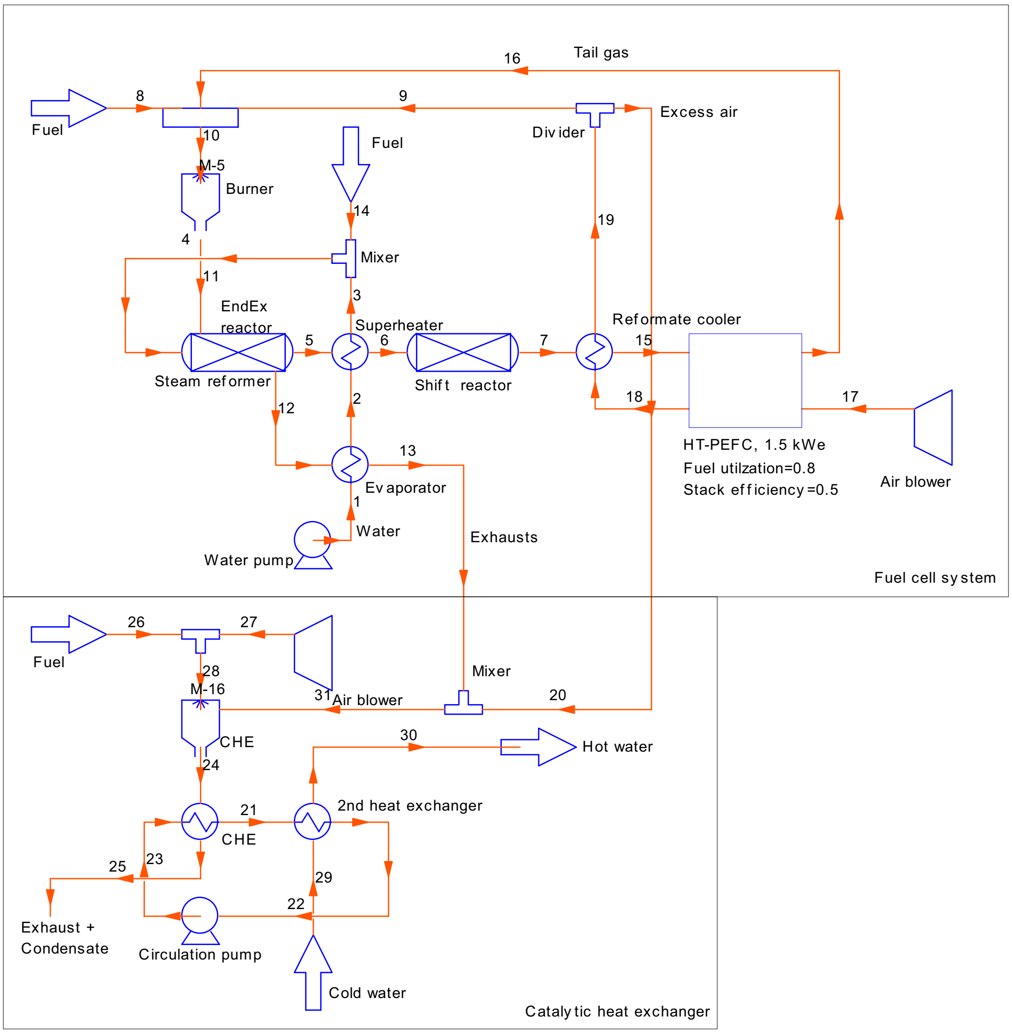

Figure 13 Process scheme of a CHP comprising Optiformer, HT-PEFC and a Catalytic heat exchanger for supplementary heat production

As shown in the diagram, the process scheme is rather simple. The calculations show that the overall electric and thermal efficiencies are 35 and >95%, when natural gas is used as the fuel.

Our Italian partner, ICI, is testing reactors with a capacity up to 30 nm3/hr of hydrogen in their Hydrogen R&D Lab. The coil reformer has undergone more than 100 full thermal cycles without any strength issues. Thus, there is no need to use exotic materials in the Optiformer concept since the structure has a great deal of mechanic flexibility. It is, however, important to choose material which do not pick up too much carbon from reformate gas or give rise to metal dusting.

It is possible also to implement a reactor system for preferential oxidation (PROX) of CO downstream the Optiformer unit. This reactor is preferably based on a CatHex-reactor, i.e. a catalytically coated heat exchanger, which will enable us to achieve a very accurate temperature control. Figure 14 show a PROX-unit with a capacity of 1-2 kW_e. Figure 15 shows the performance of a CatHex reactor in reformate purification. The unit was operated in a reformate gas containing 1.6% CO at temperatures around 150ºC.

In order to get below 100 ppm CO, it is necessary to arrive at conversion degrees of about 99.5%, which was possible at overall O_2:CO-ratios of 1.2 – 1.5. The most important advantage over previous PROX-designs is that only one step is required to reach acceptable CO-concentrations whereas 3 – 4 steps were used in the previous designs.

Figure 14 CatHex reactor for PROX. The reactor consists of catalytically active plates which are assembled into a plate-type heat exchanger. Volume≈0.5 litre/kW_e.

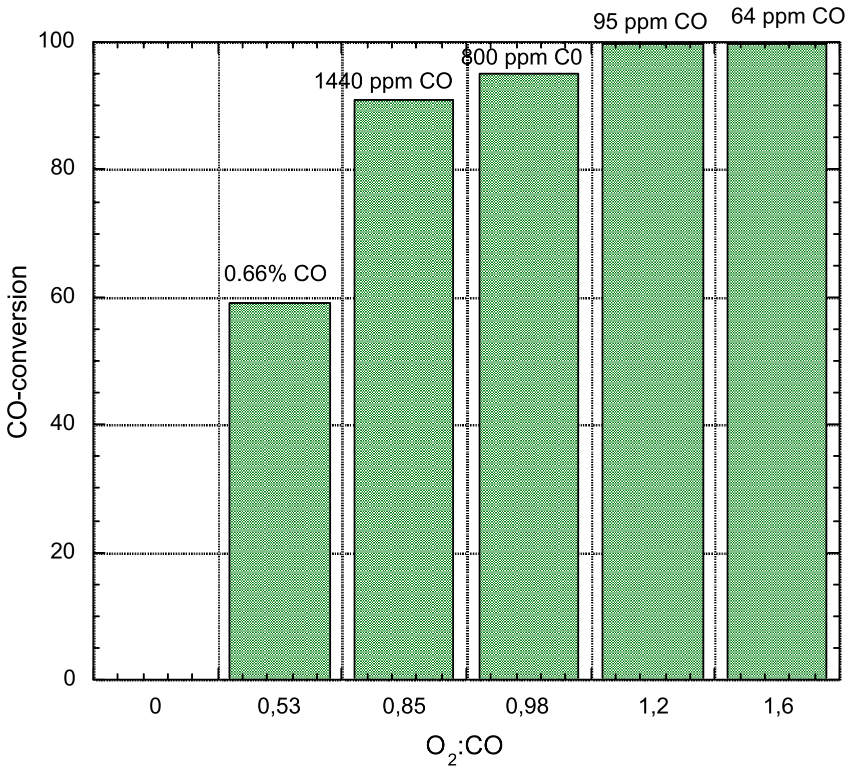

Figure 15 Performance of a 1-2 kW_e-PROX unit. CO-conversion versus O_2:CO-ratio at 150ºC. Inlet-CO concentration: 1.6% (v).

Consequently, if the Optifomer unit is complemented with said PROX-reactor this concept can be used also in systems comprising LT-PEFC units. LT-PEFC units might have an interest in cases where simple hydrocarbons like natural gas, biogas and alcohols are processed. In cases with more complicated hydrocarbons, we believe that high-temperature fuel cells are will provide simpler and more efficient systems.

7. Conclusions

It can be concluded that the re-designed reformer unit (Optiformer) provides a number of advantages over the previous Ultraformer concept. The unit is much easier to manufacture and can be produced from ordinary high-temperature stable steel alloys. The major drawbacks of the Ultraformer were associated with manufacture complexity and problems with thermo-mechanical stresses during rapid heat-up and cool down, i.e. thermal cycling. The Optiformer is not sensitive to such phenomena since the hot structure, i.e. the reformer coil, has a flexible design and can move freely when exposed to thermal load.

The Optiformer can be started within a minute and it not necessary to restrict the temperature raise rate or to limit the inlet temperature to the coil section as in the case of the Ultraformer unit.

The Optiformer concept has been subjected to more than 100 full cycles thermal without any thermo-mechanical issues and equilibrium conversion is reached with respect to the fuel. Since it is possible to use considerably higher operation temperature in the coil section in comparison to the heat-exchanger section of the Ultraformer, the conversion degree is normally close to 100%.

The Optiformer unit is highly integrated with respect to evaporators and heat recovery structures and is also internally insulated and jacked cooled. This means that the skin temperature of the unit is around 100°C even if the internal coil temperature close to 1000°C.

Furthermore, the Optiformer unit is equipped with a water-gas step to reduce the CO-concentration to levels acceptable for the high-temperature PEFC-concept. The next planned step is to integrate the Optiformer unit with a high-temperature PEFC unit to provide a complete CHP-unit in the 1 –2 kW_e-class. In this project we have demonstrated operation with natural gas and kerosene but the unit can also operate on other fuel gases like biogas and LPG. As liquid fuels, it is possible to consider a great variety of fuels ranging from alcohols to diesel.

The combination of an Optiformer unit and high-temperature PEFC will provide a simple and durable system for small-scale production of electricity and heat.

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