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Auxiliary power unit based on a solid oxide fuel cell and fuelled with diesel

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Abstract

An auxiliary power unit (APU) is presented that is fuelled with diesel, thermally self-sustaining, and based on a solid oxide fuel cell (SOFC). The APU is rated at 1 kW electrical, and can generate electrical power after a 3 h warm-up phase. System features include a "dry" catalytic partial oxidation (CPOX) diesel reformer, a 30 cell SOFC stack with an open cathode, and a porous-media afterburner. The APU does not require a supply of external water. The SOFC stack is an outcome of a development partnership with H.C. Starck GmbH and Fraunhofer IKTS, and is discussed in detail in an accompanying paper.

Keywords: APU; SOFC; Diesel reformer

1. Introduction

Users of cars and trucks continually expect higher levels of comfort and ease of use. This has led to increasing requirements for on-board electrical power [1]. The use of electrical equipment, e.g. electrical air conditioning on-board of vehicles during engine stand still is limited due to the batteries capacity. The only viable energy storage that can supply such consumers is the liquid fuel in the cars tank. A fuel cell-based auxiliary power unit (APU) is one possible method of supplying this electrical power. An APU based on a solid oxide fuel cell (SOFC) is theoretically capable of producing electricity with a higher efficiency than an alternator linked to the primary traction engine. Such an APU would be fuelled from the same source as the traction engine, namely diesel or gasoline; would not have any other special requirements, such as an external supply of water.

Webasto AG is an automotive supplier that has been developing a diesel fuelled APU since June 2002. This paper presents the experimental results from the latest APU system prototype.

2. System philosophy

A system design philosophy provides a context in which to make design decisions. Webasto's APU system design philosophy focuses on simplicity, cost, durability, and is driven by the requirements of an automotive environment. A system design (or top-down) approach is fundamental, providing clear paths for resolving conflicting component requirements.

The basic concept of an APU is an efficient, quiet, vibration-free, and ultra low emission source of on-board electrical power. Similarly to other analysis [1], the two basic options for fuel cell-based APUs were identified as SOFC or polymer electrolyte membrane fuel cell (PEMFC).

A SOFC-based system was selected over PEMFC, owing to clear paths for future cost reductions, and to simpler, more robust system designs. PEMFC systems require clean hydrogen reformate with a relatively complex clean up process on different temperature levels. In SOFC systems the major components operate at the same temperature level and can be easily integrated into one hotbox.

Diesel was selected as the fuel, for ease of entry into the truck market and niche applications such as leisure and military systems. An external water supply was rejected to reduce system costs and to eliminate failure modes.

Analysis of on-board electrical requirements led to a target electrical power of 2–5 kW. This power is sufficient to supply electrical equipment for driver conveniences (air conditioning, microwaves, TV) on-board of trucks and cars during engine stand still and to provide a substantial quantity of highly efficiently generated electrical power to the power net of vehicles while driving.

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System simulation and experimental results of basic components indicate that a peak electrical efficiency of 30% with respect to the LHV of diesel is a realistic but not too aggressive target. Even 20% efficiency is fine for most applications with respect to efficiencies of motor driven APUs.

To minimize system costs a standard blower should provide the air for the three major components (reformer, SOFC-stack and afterburner). To apply a standard blower the overall pressure drop of the system should not exceed 100 mbar. A minimum pressure drop is a basic design requirement for the component development.

The APU system was pared down to minimum; reformer, stack, afterburner with heat exchanger and air management. This was input to the system simulation, and the design of the first prototype.

3. System simulation and control

System simulation provides more detailed analysis and confirms that basic system design is sound. A mathematical model of the APU was created in order to evaluate the mass- and energy fluxes in the system. The simulation tool Matlab/Simulink was applied. The model is scalable for system net powers between 1 and 5 kW. In Fig. 1 the Sankey diagram of the 1 kW model APU is shown. Boundary conditions for the simulation include an anode off-gas recycling rate of 20% with reference to the total reformer mass flow and a specific stack performance of 300 mW cm^{-2}.

4. Prototype system

The first “system” prototype was demonstrated in June 2002, and showed that SOFC stacks could be fuelled with diesel reformate. The system included a diesel reformer and a five cell SOFC stack. The reformer and stack were integrated in a single enclosure, but were thermally isolated. The reformer was rated at 15 kW thermal, and therefore produced too much reformate for the five cell stack. To allow the majority of the reformate to bypass the stack, valves and a bypass line were introduced between the reformer and the stack. The valves had an upper temperature limit of 500 °C, forcing the reformate to cool down before entering the stack. The reformer employed a high-pressure pump and nozzle spray, which is not appropriate for an APU. The stack was thermally controlled using electrical heating elements. Stack degradation was observed, and attributed to soot generation in the cold valves. Fig. 2 shows this first system prototype.

5. Prototype APU

5.1. Design targets

The primary design targets for the prototype APU described here are:

- thermal self-sustainability; defined as stable system operation without the use of electric heating elements to maintain the SOFC operating temperature,
- 1 kW rated stack power.

Secondary design targets included:

- external wall temperatures <50 °C,
- system volume <120 L,
- ease of manufacture, assembly and maintenance.

The system volume target was deliberately relaxed to provide opportunity to maximise the ease of assembly and maintenance. The focus was on functionality as opposed to minimal volume and highly integrated construction. In this context a simple flow diagram was preferred and the application of cathode exhaust recuperator and anode off-gas recirculation injector were shifted to the next system generation.

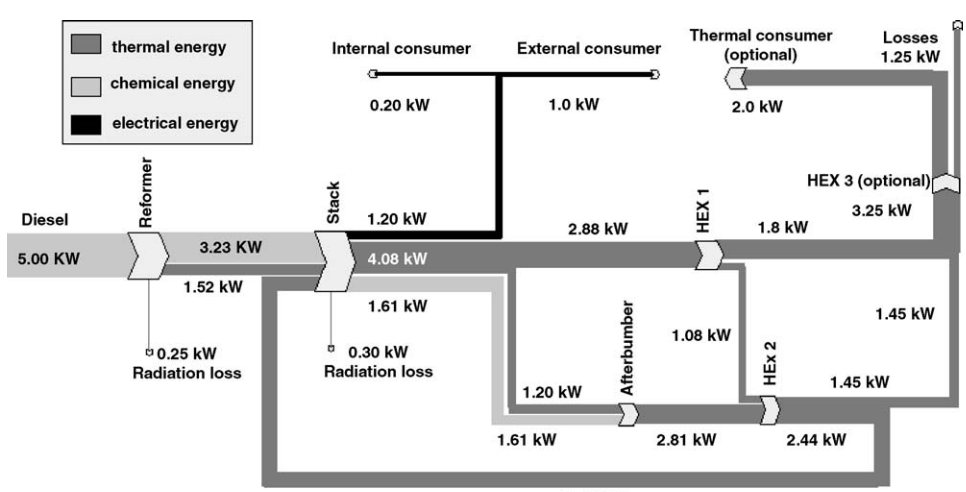

Fig. 1. Sankey diagram of 1 kW APU.

Fig. 2. Webasto system prototype.

5.2. System description

The system is divided into three temperature zones:

- high temperature hotbox with reformer, stack, afterburner and heat exchanger (~850 °C, 68 L),
- medium temperature with bypass valves (~500 °C; 16 L),
- ambient temperature with blower, air management and controls (ambient; 36 L).

The APU system schematic is presented in Fig. 3, and the hotbox internals are shown in Fig. 4. The total system volume is below 120 L. The target is to completely remove the medium temperature zone in the next system generation.

The APU also provides a platform for the development of basic control strategies. For safety reasons and protection of expensive prototype stacks an electrical heating system for the hotbox and bypass valves around the stack are provided.

Diesel is supplied to the reformer using diesel pumps using open-loop control, with the option to switch to closed-loop control. The same philosophy applies for the blower control and air management.

5.3. Reformer

The patented reformer is a catalytic partial oxidation (CPOX) type reformer with a total oxidation zone supplying hot gas to a second fuel injection zone. The mixture of hot burned gas and

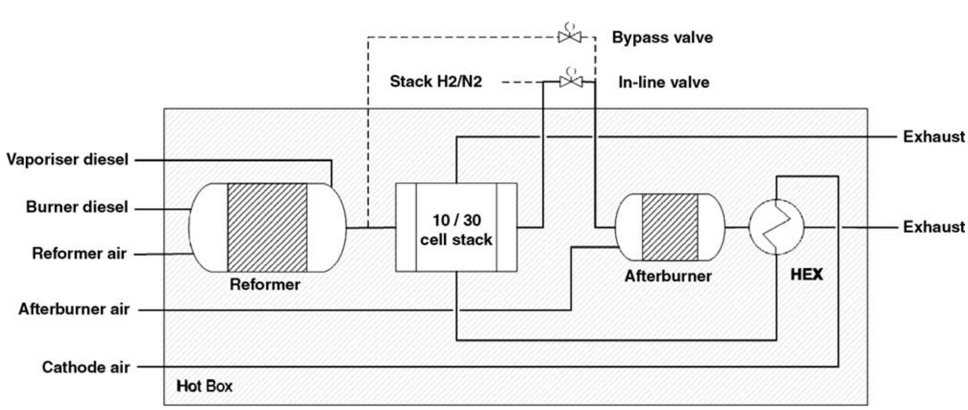

Fig. 3. APU system schematic.

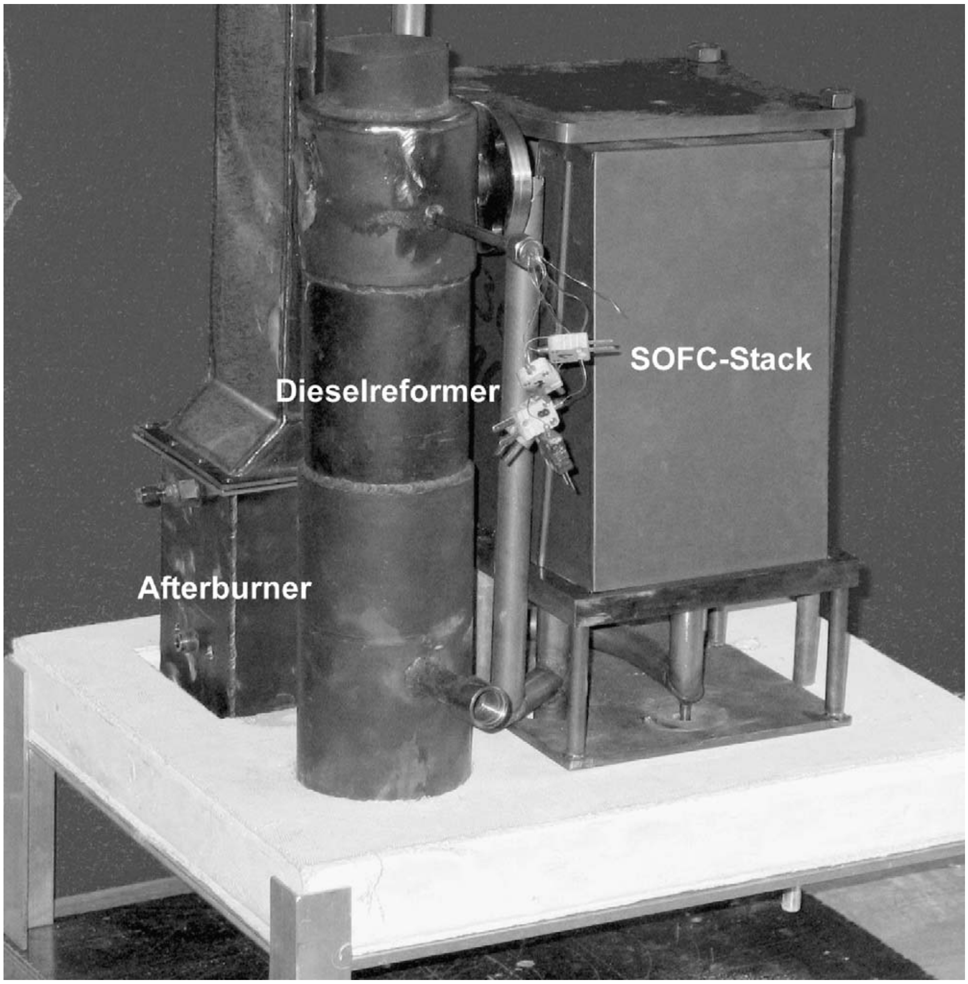

Fig. 4. Hotbox internals.

vaporized diesel then flows through a reforming catalyst. The flame in the total oxidation zone supplies thermal energy to the catalytic reforming zone via conduction. Standard components from the heater business of Webasto are used within the reformer, such as burner bodies and diesel evaporators. The reformer does not use an external supply of water. The reformer was at all times fuelled with low sulphur diesel.

5.4. Stack

The SOFC stack used in the APU was developed in partnership with H.C. Starck GmbH and Fraunhofer IKTS (Institute for Ceramics Technology and Sintered Materials). The stack features redox tolerant electrolyte supported cells, and an open cathode. The stack module is described in detail in an accompanying paper [2].

5.5. Afterburner with cathode heat exchanger

The afterburner is the last component before off-gases leave the system. The burner has to meet all requirements of power and system transients. A porous media burner was developed for its wide power and lambda range and stable operation during transients. The target for exhaust emission is to be as low as stationary residential heating systems.

Two basic concepts were tested for gas mixing before entering the porous media: homogenous mixing below the ignition limit plus flame arrestor, or non-premixed planar burner in contact with porous media. The non-premixed concept has advantages over the premixed concept because of its independence from inlet burner air temperature. This gives more flexibility in system operation and control.

The premixed burner is limited to a maximum premix temperature of ∼300 °C. Above this limit the flame burns back into the mixing zone while critically overheating and destroying the flame arrestor. To prevent this occurring, one has to operate the burner at a much higher lambda than the non-premixed burner. This reduces the flame temperature, heat exchanger efficiency and start-up time of the system, while increasing CO emissions. However, the results presented in Section 6 of system operation are from a premixed burner and should represent the worst case of system behaviour.

A planar heat exchanger is added at burner exhaust to heat up the cathode air from ambient to stack entrance temperature (650–800 °C). A relatively simple geometry is sufficient to heat up the cathode gas amounts in a 1 kW system.

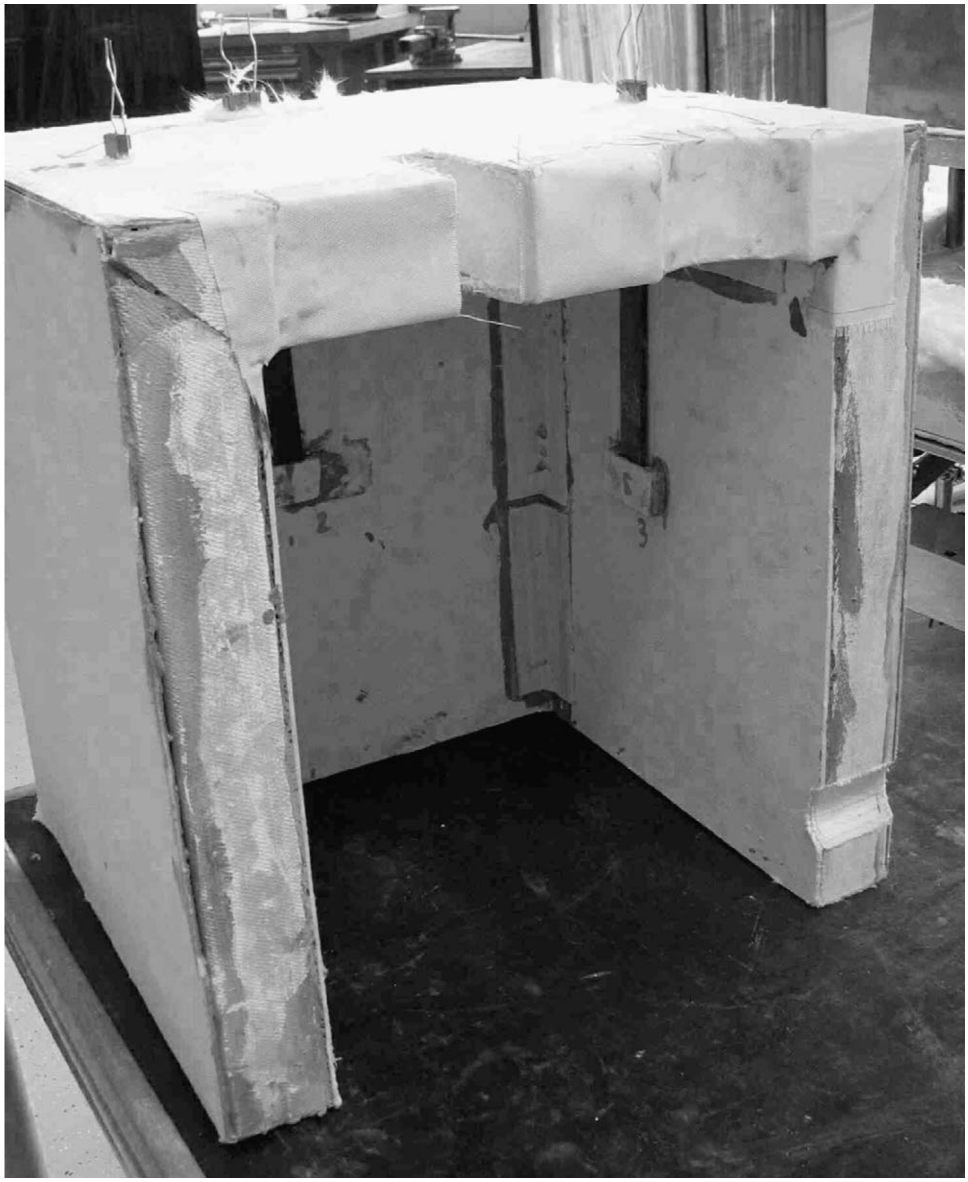

Fig. 5. Hotbox.

5.6. Hotbox

The hotbox is a simple design manufactured from 44 mm microporous insulation and lined with 3 mm thick sheet ceramic (Fig. 5). High temperature adhesive is used to bond the components, thereby providing good structural stability. The design is oriented on ease of assembly, disassembly, modification and repair. The all-ceramic construction requires only simple hand tools, and the turn-around time for repair is less than a day. The overall hotbox surface area is ∼1 m^2. This is important for heat loss discussion.

6. Experimental results with 10 cell stack

The APU was designed to operated with a 1 kW 60 cell stack, but to date has only been tested with a 10 and 30 cell stack. This section describes results from operation with the 10 cell stack, including start, operation and shut-down procedures. During this phase, the APU was exposed to over 10 thermal cycles and over 5 redox cycles. Prior to installation in the APU, the 10 cell stack was operated on a stack test stand, and had been exposed to over 10 thermal and redox cycles.

6.1. “Safe” system start

To start the APU, the reformer burner is used as a heater. This produces exhaust gas at lambda 1.1, which is able to oxidise the anode. To protect the stack, the in-line valve is closed and a small flow of purge gas is supplied to the stack. The purge gas flows in a reverse direction through the stack. The hot reformate gas exits the hotbox to bypass the stack, then re-enters the hotbox via bypass valve and the afterburner. The hotbox is heated by radiation and convection from the hot reformer. When the reformer catalyst is over 800 °C, reforming is started by introducing diesel

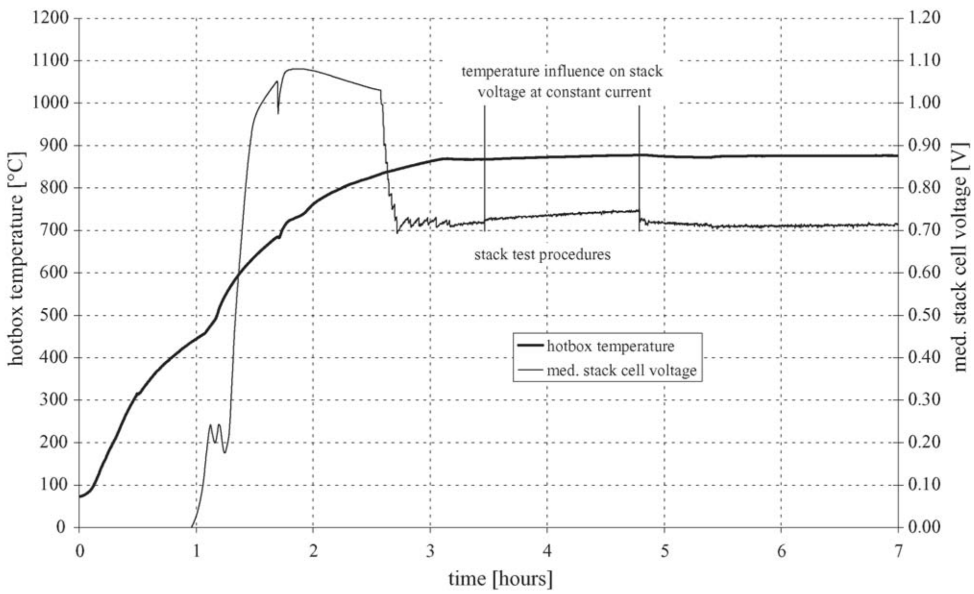

Fig. 6. Hotbox temperature and stack cell voltage during "safe" start-up.

to the vaporizer zone of the reformer. This produces reformate at lambda ~0.55, which is oxidised in the afterburner. The system is then stabilised at 850 °C, and reformate is supplied to the stack by opening the in-line valve. The described procedure takes more than 3 h, however current can be drawn from the stack after less than 3 h when the stack temperature reaches 700 °C.

Fig. 6 shows the results for the "safe" start procedure. The hotbox temperature can be seen rising smoothly, then stabilising at ~850 °C. The cell voltages increase to the classic open circuit voltage (OCV) when the cell is warm enough to become ionically conductive, and then falls to ~0.7 V when current is drawn.

6.2. "Real" system start

The APU can be started without purge gas, and without assistance from electrically powered heating elements in the hotbox. As described above, the reformer burner is used as a heater. The produced exhaust gas flows directly through the stack. The bypass valve remains open, allowing some gas to bypass the stack, as the 10 cell stack has insufficient capacity for the entire flow rate. The split between stack flow and bypass flow is not known, but could be evaluated by means of known performance of the stack with respect to different utilizations. The hot gas warms the stack and hotbox. The reformer power is adjusted to maintain a 200 °C temperature gradient across the anode.

When the stack reaches 500 °C, the reformer switches to lambda 0.55, and the afterburner is started. This reduces the anode, and allows the cathode air to be heated. The stack and hotbox are then warmed up to 850 °C. Current is drawn when the stack reaches 700 °C, which also assists with the stack heating. Note that the reformer is switched to lambda 0.55 earlier than in the "safe" start procedure. This cools the catalyst below the desired operating temperature, and increases the risk of soot formation. This did not appear to damage the stack.

Using this start procedure, the stack generates the same power as with a "safe" start procedure. Fig. 7 shows the results for the "real" start procedure. The start switch from lambda ~1.1 to ~0.55 can be clearly seen at the indicated time of 2 h, where the cell voltage increases suddenly. The decrease in cell voltage at 2.7 h shows that current is being drawn from the stack, when the stack base temperature is 740 °C.

The stack was operated after this procedure at the same temperature and current as after the "safe" start procedure and produced the same power. This can be seen by comparing stack cell voltage at continuous operation in Figs. 6 and 7.

6.3. Stable system operation

The APU (with 10 cell stack) has been operated stably for over 14 h with real diesel reformate without any observed degradation. Fig. 6 shows a 4-h period of operation on diesel reformate. Some drift can be observed in the hotbox temperature hence a drift in cell voltage.

The hotbox temperature can be controlled by altering cathode air flow rate or the reformer power. In a production APU, reformer power is linked to stack output, so reformer power is only a viable temperature control strategy for prototypes with small stacks and low system efficiencies.

The system and stack temperatures respond slowly to changes in cathode air (minutes, not seconds). Therefore, cathode air was not used as a control function with the 10 cell stack. The system response to cathode air flow should improve with larger stacks, as they would dominate the thermal balance of the hotbox.

Fig. 8 demonstrates the ability to control hotbox temperature with reformer power. Between the indicated time of 0 and 4 h, the reformer power increases to steadily warm the hotbox. Similarly, between 4 and 6.5 h, the hotbox temperature can be seen to follow the reformer power.

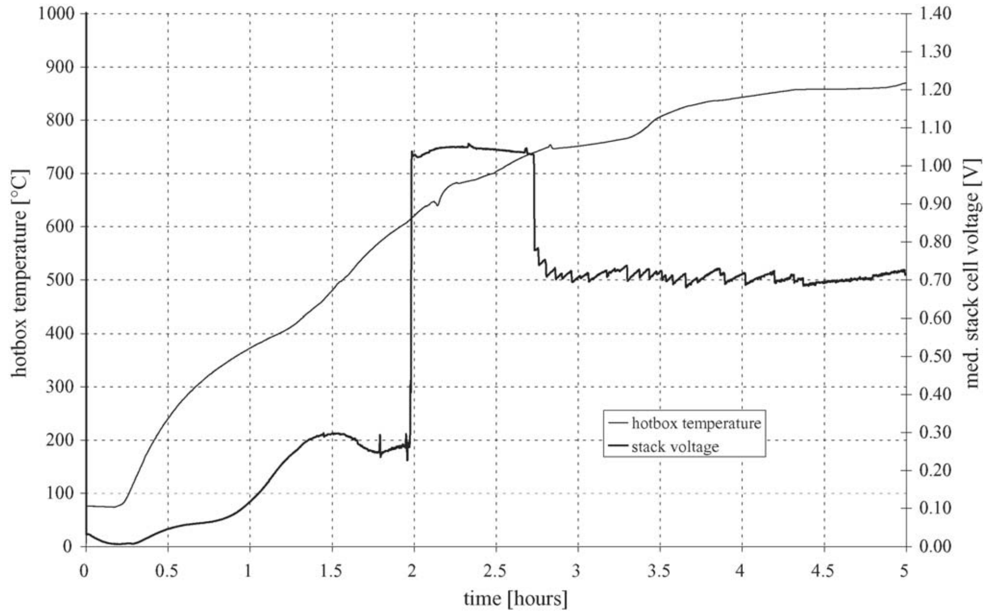

Fig. 7. Hotbox temperature and stack cell voltage during “real” start-up.

6.4. System stop

The APU is stopped by isolating the stack with purge gas, and then switching off the reformer and afterburner. A small flow of cathode air is maintained, so the cathode is not reduced by gas leaks from the anode. The hotbox then cools slowly. The APU can also be stopped with an emergency procedure. This is simply the shutting off of all inputs, both air and diesel, at the same time. The system is then left at rest to cool slowly. Diffusion of oxygen slowly oxidises the anode. Fig. 9 shows the real cool-down temperature profiles and the ideal case at same conditions.

Comparing the cool down curves one can see, that even the forced cool down is not so much faster than cool down by free convection. This means that heat losses at higher temperatures from bad insulation are of higher order of magnitude than heat losses from forced convection. The calculated ideal curve shows cool down with perfect insulation at given conditions with a heat transfer coefficient of $0.023\,W\,m^{-1}\,K^{-1}$. In a production APU the system will be packaged much closer and the surface area of the hotbox will be much smaller. The cool down curve is a strong function of surface area hence after a system shutoff the system is kept hot for a long time with the ability for rapid start-up.

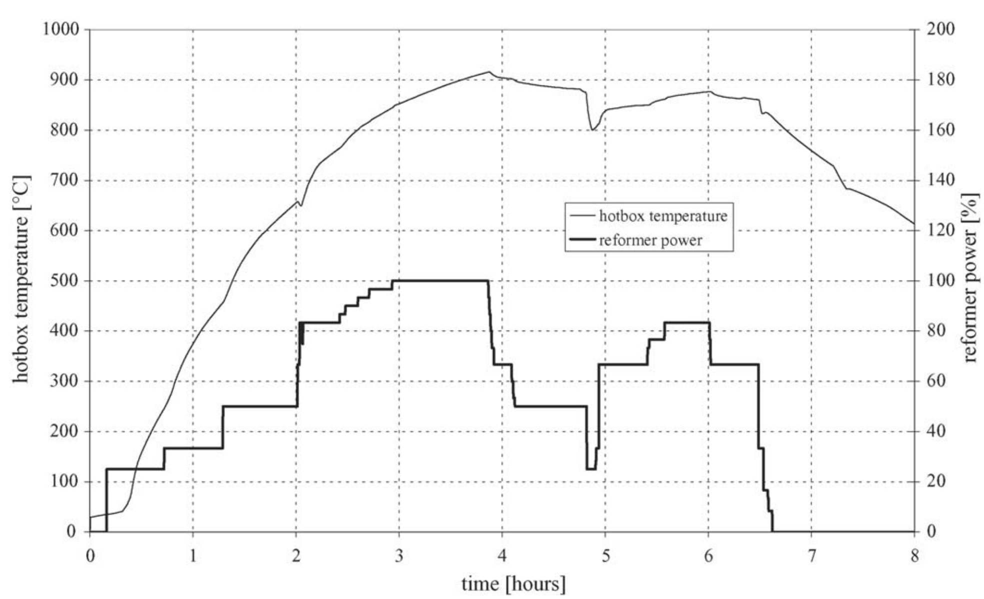

Fig. 8. Temperature response of hotbox on reformer power.

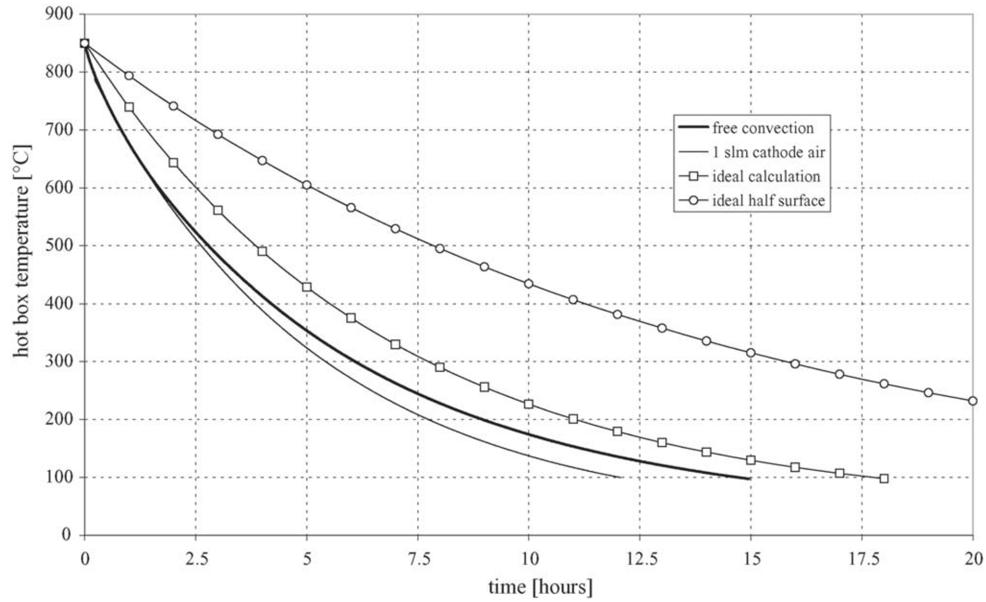

Fig. 9. Hotbox slow and forced cool down to 100 °C.

Fig. 10 shows a fitted cool down simulation and calculated heat losses with respect to the hotbox temperature. The calculation was fitted by only changing the heat transfer coefficient of the insulation. For the cool down calculation a relatively simple method was applied to estimate the heat losses, see Eq. (1):

$$T_{\text{hotbox}} = T_{\text{ambient}} + (T_{\text{start}} - T_{\text{ambient}}) \exp(-tC) \quad (1)$$

T_{hotbox} is the hotbox temperature (as a function of time), T_{ambient} the temperature of the surrounding air, T_{start} the hotbox temperature at the beginning of the cooling process (nominally 850 °C), and t is the time. The system constant C contains the heat transfer coefficient, system mass, surface area and specific heat of the hotbox internals.

7. Experimental results with 30 cell stack

After demonstrating the basic operation of the APU, the 10 cell stack was replaced with a 30 cell stack. The electrical heating elements were also removed from the hotbox. To date, the 30 cell stack has also been exposed to over 10 thermal and redox cycles. Peak stack power has been observed as 420 W, with the reformer operating at 4 kW, lambda ∼0.55.

7.1. Stable system operation

The 30 cell APU has also been operated stably for periods over 4 h, as illustrated in Fig. 11. During this test, the reformer

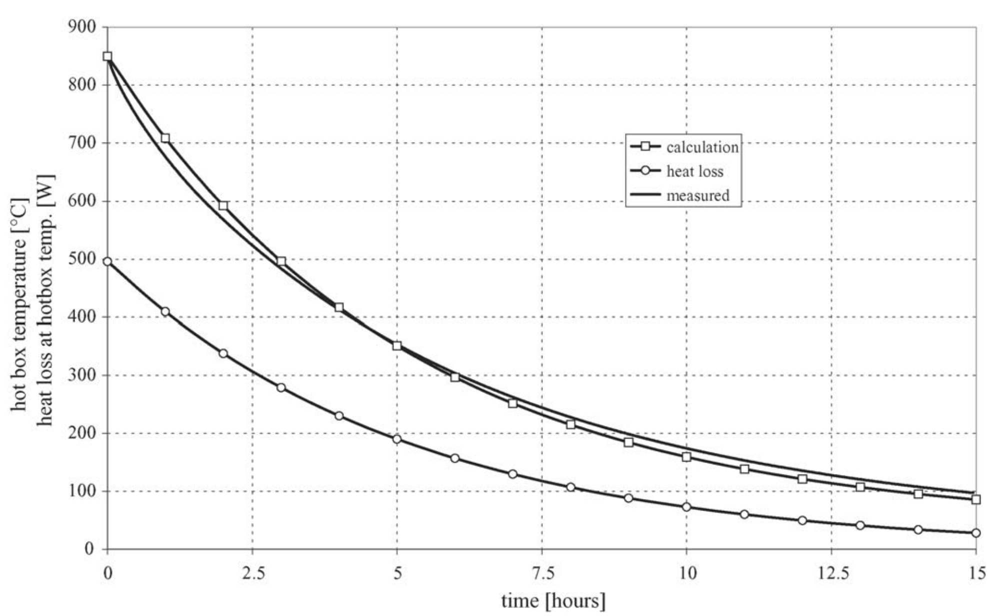

Fig. 10. Hotbox cool down simulation and heat loss.

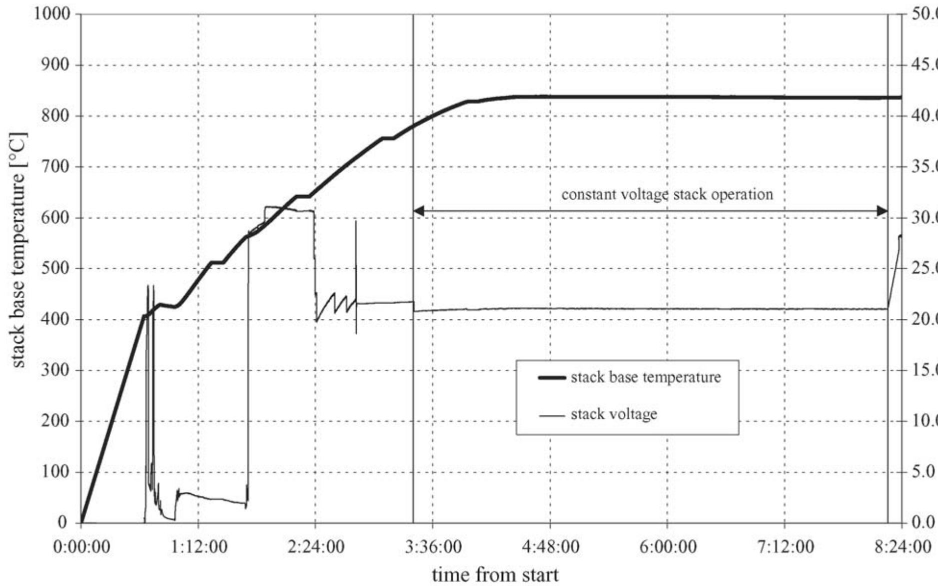

Fig. 11. Stable system operation with 30 cell stack.

was supplied with 3.6 kW of diesel, and the stack produced over 360 W of electrical power. All reformate flowed through the stack. The maximum pressure in the system is located at the reformer air inlet, and during normal operation was always less than 30 mbar.

7.2. Stack current transient

The APU is able to operate stably despite transient disturbances, including step changes in stack current or reformer power. This tolerance to transients is predominantly a function of the afterburner. In a production APU, this tolerance will allow faster system state changes, and reduction in the quantity or cost of sensors.

Fig. 12 shows the response of afterburner temperature to a step change of stack power from full load to zero and back. As expected, the afterburner exhaust increases in temperature when stack current is removed, owing to the increase in chemical energy supplied to the afterburner.

Fig. 13 shows the APU test stand set-up. The electrical control rack is shown at far left, and is based on LabView and National Instruments PXI and SCXI hardware. The gas rack is at cen-

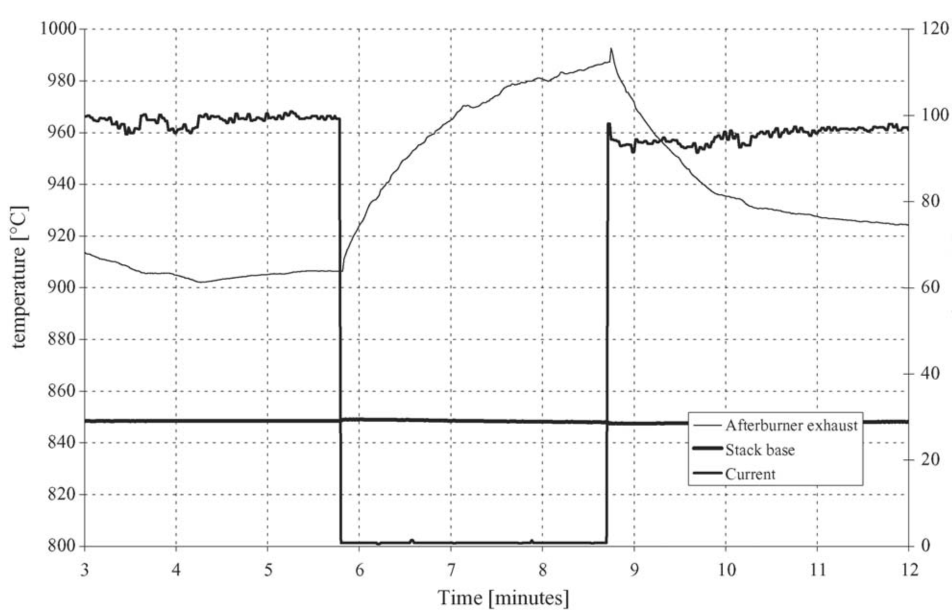

Fig. 12. System response to stack current step change.

Fig. 13. APU test stand.

tre left, which provides air, hydrogen and nitrogen to the APU itself, shown at centre right. The current sink is shown at far right.

8. Conclusions

An APU that is based on a solid oxide fuel cell and fuelled with diesel has been designed, constructed, and tested. This prototype APU demonstrates several key features required of a production APU; namely thermal self-sustainability, operation without an external supply of water, start up without electrical heating elements or purge gas, tolerance to system transients and an emergency shut-down process.

The APU has been operated stably for durations over 4 h, without observable stack degradation, demonstrating that the "dry" CPOX reformate is acceptable to the stack. No soot has been observed within the stack or hotbox.

A top-down system design process was used to produce the APU, resulting in a simple system design, with the three primary components of a SOFC system; namely reformer, stack and afterburner; integrated into a single hotbox. Thermally self-sustaining operation is possible with stacks of only 10 or 30 cells, and the system responds stably to interruptions such as step changes in stack current. The temperature within the hotbox can be controlled by altering the flow of diesel entering the system (reformer power). Finer but slower control can be obtained by altering the cathode air flow rate.

The redox tolerant stack allows significant simplification of the start-up, shut-down, and emergency shut-off procedures. The open cathode and low pressure drop within all system components produced a total system pressure drop of less than 30 mbar.

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