Ref. Ares(2022)4588463 - 22/06/2022

Deliverable 4.4

Design study for pressurised 50-100 kW HT-PEMFC system

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Deliverable due date: 31.3.2022

Deliverable submission date: 22.6.2022

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This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under Grant Agreement No 875081. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research.

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Nomenclature

A	cell active area [cm^2]
a	scale-up factor [-]
C_P	specific heat capacity
F	Faradic constant [C mol^{-1}]
I	current [A]
j	current density [A cm^{-2}]
M	molar weight [g mol^{-1}]
$\dot{m}$	mass flow [kg s^{-1}]
N	number of units [-]
$\dot{n}$	molar flow [mol s^{-1}]
R	Gas constant [J mol^{-1} K^{-1}]
P	power [W]
p	pressure [Pa, bar]
T	temperature [K, °C]
U	voltage [V]
γ	heat capacity ratio [-]
η	efficiency [-, %]
ϵ	performance improvement [-, %]
λ	excess ratio [-]
μ	performance loss factor [-]

Background and objectives

This report details the design study for pressured 50-100 kW HT-PEMFC system. The stack module developed by Blue World Technologies (later BWT) is expected to gain significant power density improvement because of pressurisation. However, the pressurisation of the stack requires an energy consuming compressor unit, adaptation of which could lead the system level efficiency gain to be minimal or even negative. Therefore, to eliminate this challenge a pressure energy recovery unit, an expander, is essential for the overall system.

In the work task described by this report, the focus was on the development of the pressurisation model for cathode side of the HT-PEMFC stack system. On operation point of view, the most relevant limiting factor for the pressurisation is the tolerance of differential pressure of MEA, which has been determined to be few hundred millibars.

Target of this work task was to model the effect of the stack pressurisation to the system level efficiency. For the pressure energy recovery, the target of the total electrical energy efficiency increase was set to be 2-3 %. The model was developed for 50 – 100 kW scale HT-PEMFC stack system and it was based on the data provided by BWT.

As a separate subtask for development of the pressure energy recovery model, to gain efficiency improvement for the stack system, selection of thermoelectric generator (TEG) modules for stack systems was done.

Main objectives in the design study for pressurised the 50-100 kW HT-PEMFC stack system included

- developing a pressure energy recovery model using the BWT stack performance data
- based on simulation results, evaluation, and discussion on the benefits of the pressurisation of 50-100 kW stack
- the selection of TEG modules for 5-10- and 50-100-kW systems

Pressure energy recovery model

Based on 5-10 kW scale stack performance data, the effect of pressurisation into system level efficiency was modelled. In the pressure energy recovery model, the stack performance improvement, an energy consumption of a compressor, and an energy generation by an expander were modelled with MATLAB for a 50-100 kW stack system.

Mathematical background of the model

The performance data used in this study was from a 5-10 kW stack system developed by BWT. To simulate the performance of 50-100 kW system in atmospheric conditions, this performance data was multiplied with an up-scale factor, a, and a performance loss factor, μ_{loss}. Values for these factors were fixed to be 10 and 0.9 respectively. Therefore, when system was upscaled by factor 10, its performance was expected to match with system which would be upscaled by factor 9. The performance increase of up-scaled stack is represented in the flowing equation.

$$P_{10^1\text{ kW scale press stack}} = a \cdot \mu_{\text{loss}} \cdot P_{10^0\text{ kW scale press stack}}$$

To simulate the effect of the pressurisation of the stack, a performance data of pressured single cell tests was used. Cell voltage improvement of a single cell was calculated as linear improvement of performance. This was an assumption made to cover the test matrix conditions with existing data.

$$U_{\text{impr 0.1 bar}} = \frac{U_{\text{at }p_{\text{over}}} - U_{\text{at 1 atm}}}{p_{\text{over}}(\text{bar}) \cdot 10}$$

The following equation was used to calculate power output of pressured 5-10 kW stack under different pressurisation conditions. The power output data was corresponded with different current densities.

$$P_{10^0\text{ kW scale pres stack}} = P_{10^0\text{ kW scale unpres stack}} + N_{\text{cells}} \cdot 10 \cdot p_{\text{over}}(\text{bar}) \cdot U_{\text{impr 0.1 bar}} \cdot j \cdot A$$

To estimate air demand of cathode side, the following upscale calculation was done. The stack specific air excess ratio was used to model the system with realistic flow rates. The flow rate calculations were based on fundamental electrochemistry [1] and represented below.

$$\dot{m}_{\text{air }10^1\text{ kW scale}} = a \cdot \dot{m}_{\text{air }10^0\text{ kW scale}}$$

$$\dot{m}_{\text{air }10^0\text{ kW scale}} = \lambda \cdot \dot{n}_{\text{air }10^0\text{ kW scale}} \cdot M_{\text{air}} = \lambda \cdot \frac{1}{x_{\text{O}_2\text{ in feed}}} \cdot \frac{N_{\text{cells}} \cdot j \cdot A}{2 \cdot z \cdot F} \cdot M_{\text{air}}$$

For the estimation of the power consumption of the compressor, the following equation was used [2].

$$P_{\text{comp}} = C_{\text{P}} \cdot \frac{T_{\text{in comp}}}{\eta_{\text{comp}}} \cdot \left(\left(\frac{p_{\text{out comp}}}{p_{\text{in comp}}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) \cdot \dot{m}_{\text{air }10^1\text{ kW scale}}$$

Since the expander unit is practically a reverse compressor, the equation modelling expander performance was very similar [2]. The change in mass flow of cathode side between inlet and outlet was assumed to be negligible.

$$P_{\text{turb}} = C_{\text{P}} \cdot \eta_{\text{turb}} \cdot T_{\text{out stack}} \cdot \left(\left(\frac{p_{\text{out turb}}}{p_{\text{in turb}}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) \cdot \dot{m}_{\text{air }10^1\text{ kW scale}}$$

The performance improvement of the pressurised system was evaluated with following equation.

$$\varepsilon = \frac{P_{\text{turb}} + P_{\text{comp}} + P_{10^1\text{ kW scale press stack}}}{P_{10^1\text{ kW scale unpress stack}}} - 1$$

Simulation cases

Based on the performance data set of the 5-10 kW stack system, the simulation cases were decided to cover current densities of 0.2, 0.3, and 0.4 A/cm^2. In addition, the pressurisation range was defined to be 0.1-1.5 bar(g). Therefore, in a single simulation, system performances for 45 current density-pressurisation conditions were modelled. Based on specified input values, the model calculated the performance of the system and plotted figures presenting system performance.

The variables for each simulation were:

- Cathode side pressure drop as a fixed percentage
- Efficiency of compressor
- Electrical efficiency of expander

For simulation cases, perform for this report the following test ranges were decided:

- Cathode side pressure drop: 10, 20, and 30 %
- Efficiency of compressor: 65, 70, 75, and 80 %
- Electrical efficiency of expander: 35, 40, and 45 %

Selected efficiency values for compressor and expander were based on literature review. For industrial compressors the efficiency varies in the range of 65-85 % [3]. For expanders, electrical efficiency range of 30-45 % was selected [4]. For pressure drop the fixed percentages were conservative estimations loosely based on limited pressure drop data available from small scale stack performance tests.

Results

Based on the simulations, the results of the best and worst case are presented in Table 1. For the best simulation case, the plotted results are presented in Figure 1 and Figure 2.

Table 1. Results of the best and the worst simulation case.

Case	**Best**			**Worst**		
Input parameter values						
Pressure drop	10 %			30 %		
Efficiency of compressor	80 %			65 %		
Electrical efficiency of expander	45 %			30 %		
Results (performance change)						
Current density	**0.2 A/cm^2**	**0.3 A/cm^2**	**0.4 A/cm^2**	**0.2 A/cm^2**	**0.3 A/cm^2**	**0.4 A/cm^2**
p = 0.5 bar(g)	-0.9 %	-0.2 %	+0.4 %	-4.3 %	-3.6 %	-3.1 %
p = 1.0 bar(g)	-0.7 %	+0.7 %	+2.1 %	-5.8 %	-4.4 %	-3.3 %
p = 1.5 bar(g)	-0.1 %	+1.9 %	+4.0 %	-6.6 %	-4.6 %	-2.7 %

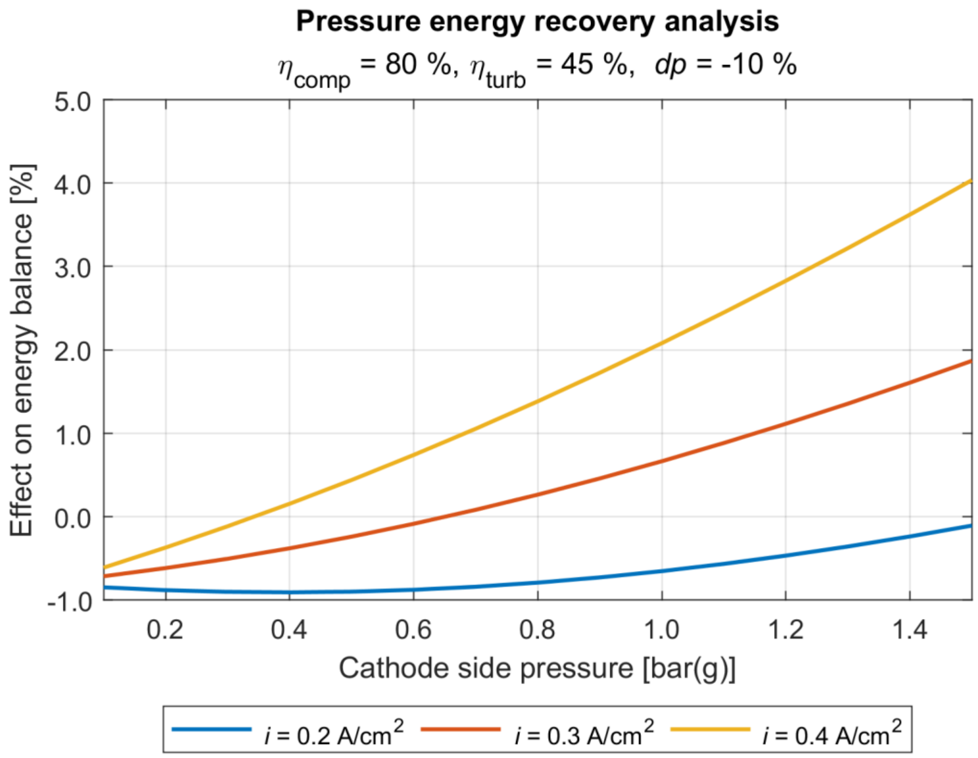

Figure 1. Effect of cathode side pressurisation on energy balance of stack system.

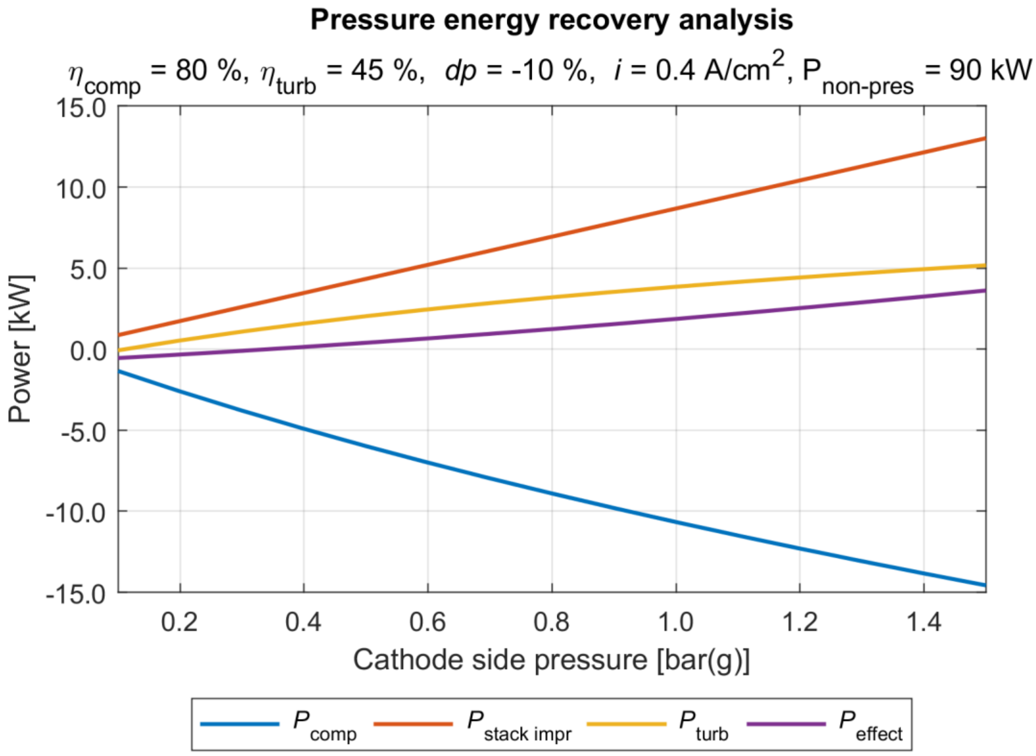

Figure 2. Effect of cathode side pressurisation on energy balance components.

Discussion

In the simulations, a significant correlation between system level performance and pressurisation rate was detected. If the pressurisation level of the cathode side remains in low levels, it is challenging to gain even minimal efficiency improvement.

Based on simulation results, the best efficiency improvement gained was 4.0 %. This means, the goal set for the pressurisation effect could be reached. However, such improvement required 1.5 bar(g) over-pressure, which would also require pressurisation of the anode side of the stack, since the BWT MEA tolerates only pressure difference of couple hundred millibars. In case of the worst simulation package, the performance effect was negative with every stack current density-pressurisation level pair. However, the results were still promising, since some conservative assumptions were made with simulation ranges and system level performance improvement due to limited source data.

The careful equipment selection can be determined to be essential for the system level performance effect. This also means, that in the system level the applied pressurisation level and current density need to be fixed, when the equipment is selected for the system.

Additionally, since the gained performance improvement remained under 5 % even in best simulation cases, a careful economic feasibility study is necessary to evaluate overall benefits of the pressurisation. Adding the compressor and the expander to the overall system increases the CAPEX, which has a direct impact on the competitiveness of the stack system.

To develop and improve the reliability of the pressure energy recovery model, the following action points are suggested:

- Utilise performance data of the 50-100 kW stack system when gained.
- Performance data of commercial or semi-commercial expanders.
- To discuss and model the role and significance of the anode side pressurisation and pressure energy utilisation.
- To study the performance of an actual compressor-expander-system, build-up of a test bench system in which compressor and expander are combined, could be considered. In such setup, the cathode side pressure drop could be demonstrated with suitable equipment.

TEG selection

Thermoelectric generators (TEG) are solid-state devices that based on the Seebeck effect convert heat directly into electric energy from a thermal gradient. TEGs generate a potential difference between to dissimilar material junctions at different temperatures. The efficiency of a TEG is normally low, approx. 5% for commercial devices, but the benefits are compactness, silent operation and the potential of using waste heat for electricity production. In the EM-POWER project, TEGs are studied as a means for increasing the system efficiency by 1-2 percentage units by using heat generated by the fuel cell system.

The first step in TEG selection was done in terms of a Master's thesis work[1]. Three commercial TEG modules from two different manufacturers were chosen based on a market research and characterized in a test bench. The chosen TEG elements are illustrated in Figure 3. The chosen modules were European Thermodynamics GM200-127-14-10, GM200-241-10-12 and Marlow TG12-8-01LS. The size of the elements was 40x40 mm and thickness 4-5 mm. The manufacturer's specified heat flux at 160 °C hot side temperature was 100 W.

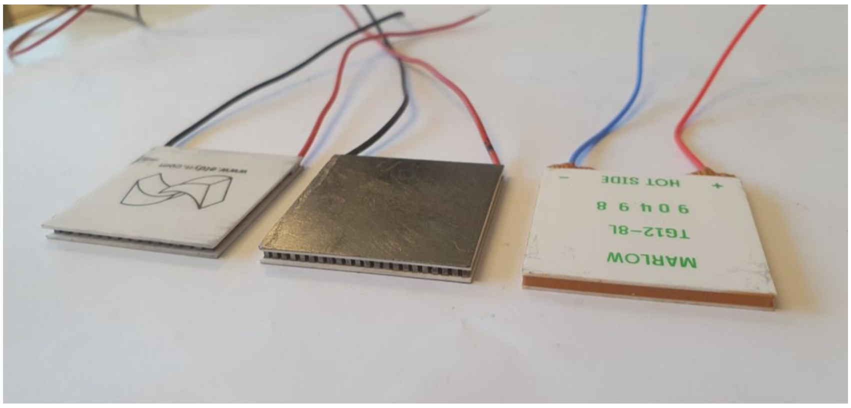

Figure 3: Three commercial TEG modules chosen for the work. Starting from left: GM200-127-14-10, GM200-241-10-12 and TG12-8-01LS.

The characterization test bench was built as a 10% scale of the 5 kW CHP system, i.e. 500 W heat was supplied to the TEGs. Five elements were connected in an array (thermally in parallel and electrically in series) adding up to a theoretical heat flux of 500 W. A thermostat supplying hot heating oil was used for the hot side and tap water was used for the cold side. Inlet and outlet temperatures were measured at both sides and the tap water flow was measured. TEGs were connected to an electric load and current and individual voltages were measured.

Figure 4 shows the output power of each studied module as function of temperature gradient. As can be seen, the power increase linearly from 4-6 W to 7-10 W per module. The European Thermodynamics' modules outperform the Marlow's TEG. However, the power output of all modules is approx. a third of the expected power, based on manufacturers' data sheets. It was noted that the compression power plays a significant role in the power production. This is clearly illustrated in Figure 5, which presents TEG output power as a function of compression pressure. Here the maximally used compression pressure is 0.18 MPa, while the manufacturer suggests compression powers up to 0.5 – 1.2 MPa, i.e. there could be even higher powers to reach. However, at higher pressures than reported, the compression plates (between which the TEG modules were placed) started to warp and destroy the module. The results show clearly that an even compression pressure and even and well aligned adjacent surfaces are paramount to reach high efficiencies with TEG modules.

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[1] Jeremias Hopsu, Development and characterization of a thermoelectric generator for a fuel cell system, Aalto University, 2021.

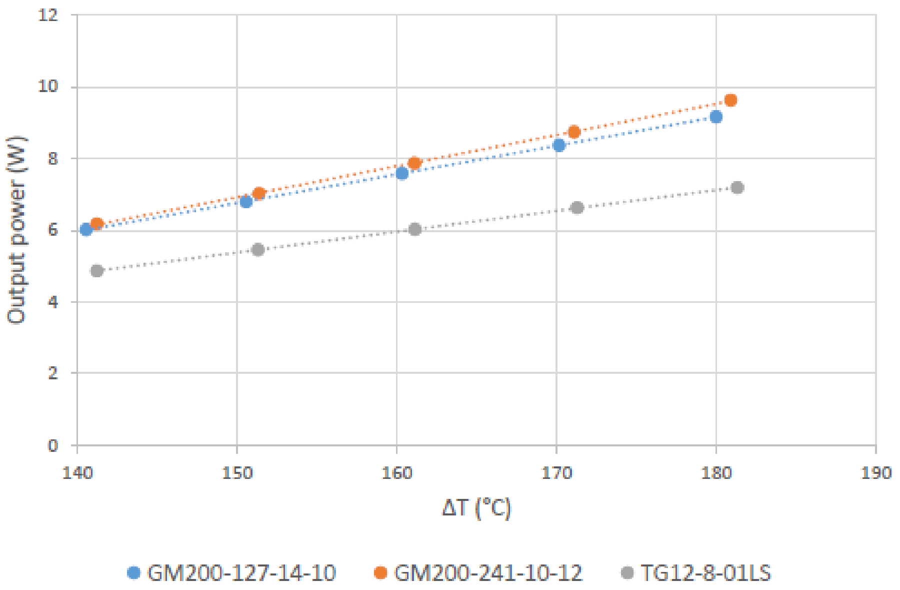

Figure 4: Output powers of the three TEGs as a function of temperature gradient.

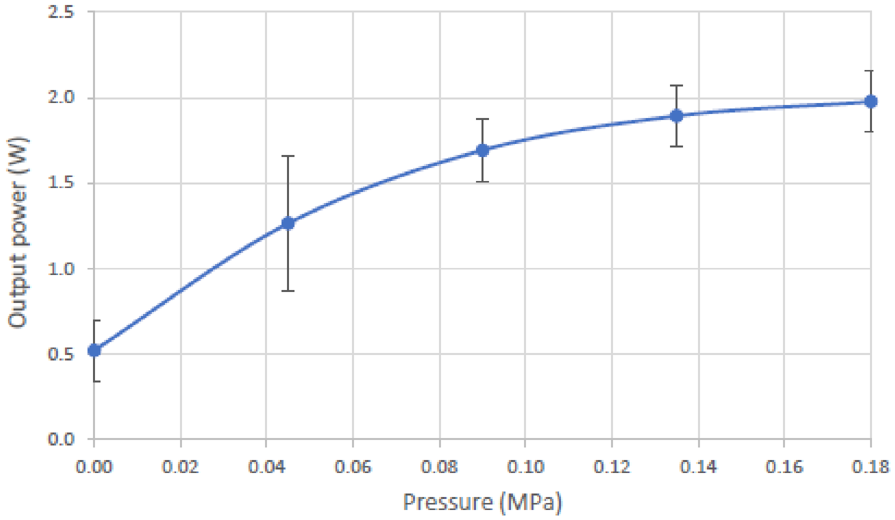

Figure 5: The effect of compression pressure on output power of a TEG module (GM200-127-14-10) with standard deviation bars.

Figure 6 shows the measured conversion efficiencies of the studied elements. The heat flux through the TEGs is calculated from cold water inlet and outlet temperatures and water flow. Depending on the module and temperature difference, the efficiency vary between 3.2 to 4%. The differences between each module are attributed to the effect of compression difference, as very small changes in compression settings of the array changed the order of performance between the modules.

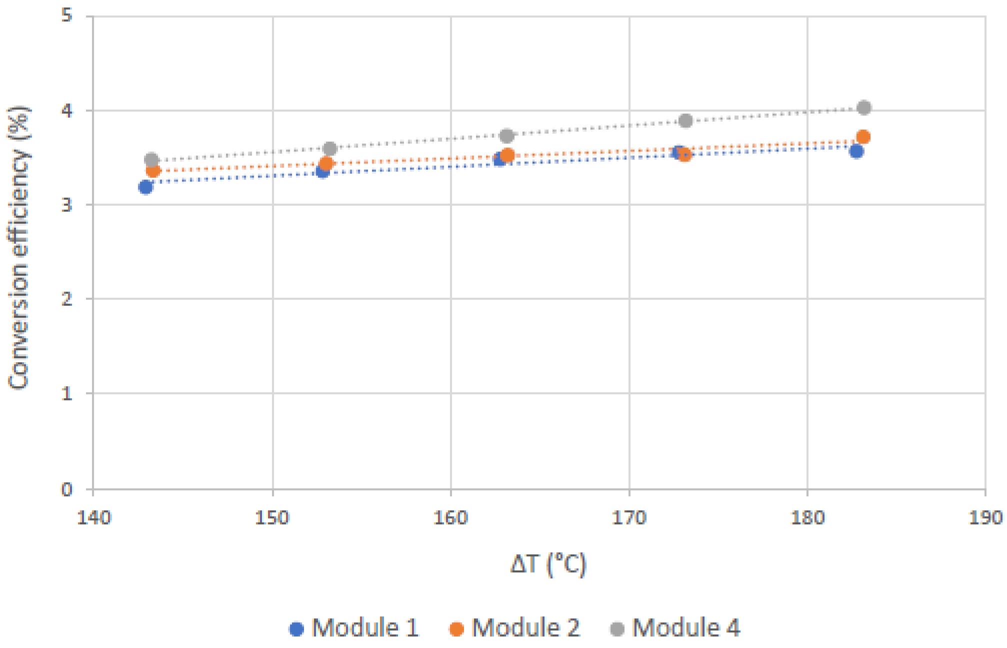

Figure 6: Conversion efficiencies for individual modules (in an array of five modules) for the best performing model GM200-127-14-10.

For the 5 kW system, no commercial manufacturer of a suitable heat exchanger TEG generators were found. Thus, an in-house design was developed and manufactured. Based on the learnings from the earlier reported prototype, strong emphasize was placed on even compression of the modules. 40 TEG modules (40x40mm) were placed between square tubes of aluminium. Figure 7 shows an end view of the TEG generator under construction. The connection points for hot and cold circuits are seen in the ends of square tubes. The middle section is for hot circuit and top and bottom sections are for cooling water/glycol. TEGs are connected electrically in series. On each TEG module there is a M10 bolt and compression spring ensuring an even and high enough compression pressure. The TEG generator is thermally installed in the cooling circuit for the fuel cell (TEG hot side) and TEG cold side is installed to the fuel cell system's external coolant circuit. Electrically the TEG is connected to the CHP system's battery management system.

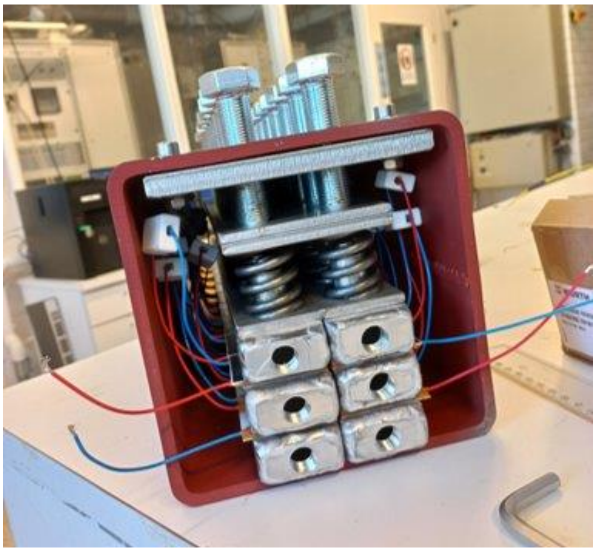

Figure 7: Photo of heat exchanger TEG for 5 kW system under construction.

Conclusions

The results given by the mathematical pressure energy recovery model were promising for the efficiency increase. However, more information related to the performance of the 50-100 kW stack system is required to improve certainty of the model. Since there is typically big difference between the electrical efficiency and the overall efficiency potential of an expander, it is urgent to have thermal management and utilisation in the overall system. In addition, a careful equipment selection is required to reach highest possible efficiencies for the expander and the compressor. To build an economically efficient pressure recovery unit, accurate modelling is required, since it makes it possible to select the equipment which would perform at their top efficiency in the fixed operation point.

TEG characterization showed that efficiencies of up to 4% were possible to reach with commercial TEG modules. The performance was highly dependent on compression pressure. Based on the pre-study, best performing modules were chosen for the TEG generator system for 5 kW CHP system. The TEG is installed as a heat exchanger between the hot fuel cell coolant circuit and the system’s external coolant circuit.

References

[1] R. O’Hayre, S. Cha, W. Colella, and F. Prinz, “Chapter 2: Fuel Cell Thermodynamics,” in *Fuel Cell Fundamentals*, John Wiley & Sons, Ltd, 2016, pp. 25–76. doi: https://doi.org/10.1002/9781119191766.ch2.

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