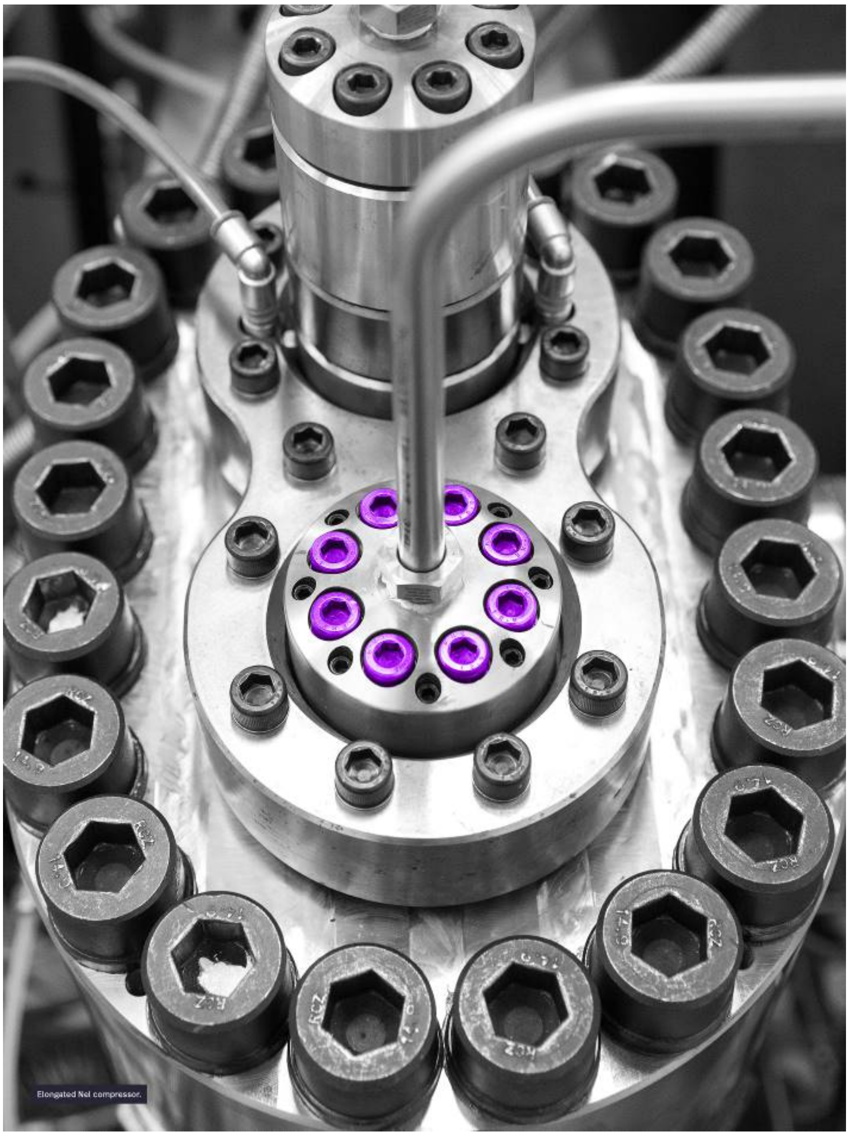
HyBoost-2

More hydrogen fueling for less

PROJECT END REPORT
JUNE 2019

Project No.: 64016-0057



SUPPORTED BY:

1. Project details

Project title	HyBoost-2 – More hydrogen fueling for less
Project identification	64016-0057
Name of the programme which has funded the project	EUDP 2016
Project managing company/institution (name and address)	Nel Hydrogen A/S Vejlevej 5 7400 Herning Denmark
Project partners	Elplatek A/S Carsten Holm A/S DTU Mechanical Engineering Teknologisk Institut
CVR (central business register)	Nel Hydrogen A/S | 26933048 Elplatek A/S | 18637189 Carsten Holm A/S | 89490812 DTU Mechanical Engineering | 30060946 Teknologisk Institut | 56976116
Date for submission (of report)	June 2019

2. Short description of project objective and results

2.1 English version

The goal of the HyBoost-2 project has been to develop and test a full scale prototype of a hydrogen compressor developed in the HyBoost-1 project supported by EUDP. A new 1st stage compressor head and supporting components has been developed and combined into a full scale compressor with double the capacity at lower inlet pressures. The compressor has successfully been tested for 4.000 hours without maintenance. Following the project Nel Hydrogen as further product matured the compressor and introduced this to markets for hydrogen refuelling stations in Europe, USA and Korea.

2.2 Dansk version

Målet med HyBoost-2 projektet har været at udvikle og teste en fuldskala prototype af an brint kompressor udviklet i HyBoost-1 projektet støttet af EUDP. Et nyt kompressorhoved til 1. stadie samt supporterende komponent er blevet udviklet og sammensat til en komplet fuldskala kompressor med dobbelt kompressionskapacitet ved lavt indgangstryk. Kompressoren er succesfuld blevet testet i 4.000 timer uden vedligehold som en del af projektet. Udenfor projektet har Nel Hydrogen foretaget yderligere produktmodning af kompressoren og introduceret denne til markedet for brinttankstationer i Europa, USA og Korea.

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3. Executive summary

HyBoost-2 has successfully managed to further advance the novel and patented compression technology for Hydrogen Refuelling Stations (HRS), developed in the EUDP supported HyBoost-1 project (64014-0556).

HyBoost-2 has developed a new 1st compressor head that enables capturing of hydrogen down to 5MPa inlet, compared to previously only 20MPa. This has enable a doubling of compression capacity achieving a similar capacity as gasoline stations per dispenser hose.

Various other components of the compressor has also been developed, both to allow dual-head operation capability and various supporting components to allow for a full integration into an HRS.

Two full scale compressor prototypes have been constructed and tested, one in laboratory and one where the compressor is integrated into an HRS. The tests validated a lifetime of 100 million compression cycles (4.000 hours) without maintenance and including 5.000 start/stops. Also hot and climate tests have successfully been conducted, respectively up to 45degC and -10degC ambient.

Nel Hydrogen has conducted product maturing activities of the hydrogen pre-compressor technology, which has enabled integration into the H2Station® hydrogen fueling station product designed for LDV fueling. A line production has been established for the compressor at existing factory in Herning, Denmark.

Securing of IPR has been an integrated part of the project and a total of four patent opportunities has been identified and specific patent applications submitted.

Since commencing of the HyBoost-2 project in 2016 the number of average employed persons (as stated in annual final report) at NEL in Denmark has grown from 50 to 85 (2018). At the time of this report issue, NEL employees 105 persons, with an expected conservative outlook of a 10% increase per year going forward, thanks to among others the results of HyBoost-2. With regards to annual revenue of NEL in Denmark this has grown from 44 million DKK in 2016 to 177 million DKK in 2018 with an expected conservative outlook of a 30% increase per year going forward, thanks to among others the results of HyBoost-2. Almost 100% of the revenue generated by NEL in Denmark is export to Europe, USA and Korea.

4. Project objectives

The objective of the HyBoost-2 project has been to further advance the novel and patented compression technology for Hydrogen Refuelling Stations (HRS), developed in the EUDP supported HyBoost-1 project (64014-0556).

Whereas HyBoost-1 achieved a laboratory prototype in scale 1:2 and a TRL-4 level, the HyBoost-2 project were to further advance the technology to TRL-6 and full-scale integration and test in relevant environment.

The previous compressor from HyBoost-1 only featured one compression head (2nd stage) which limits both the capacity and the inlet pressure range that can be served and thus range of hydrogen supply sources.

Objective of HyBoost-2 has been to develop a new 1st stage compression head that enables capturing hydrogen with an inlet down to 5MPa compared with presently only 20MPa. The combination of this new 1st stage head with the 2nd stage head is to enable a doubling of compression capacity.

HyBoost-2 has targeted conducting of the following key R&D activities:

- New 1st stage head & diaphragm
- New sealings for 1st stage piston rod and head
- New hydraulics system with dual-head capability
- New valve system with dual-head capability

In addition the outcome of the R&D activities has been aimed at constructing and testing a full-scale 1:1 compressor prototype, covering extensive tests of various endurance, stress and operational parameters, verifying reaching of the technical targets and TRL-6.

The commercial objective of HyBoost-2 has been to enable a following product maturation and inclusion in the HRS product portfolio of Nel Hydrogen beyond the project period.

The HyBoost-2 project has been led by Nel Hydrogen with participation of Carsten Holm and Elplatek, DTU-MEK and DTI. The parties together constitute advanced competences and expertise within hydrogen compression, materials, surface treatments and machining of parts.

5. Project results and dissemination of results

The HyBoost-2 project has involved the following key tasks listed below:

- Specification for global usability
- Development of compressor components for dual-head capability
- Development of components for integration into HRS
- Compressor prototype construction and tests

Results from each task is further elaborated in the sections below as well as the general dissemination activities.

5.1 Specification for global usability

The market for HRS has grown substantially the past years and specifically for NEL this has involved an expansion outside of Europe to both the USA and Korea.

Initially the intent was only to focus on Europe and USA – but as the Korean market have evolved rapidly, requirements for this market has also been taken into consideration.

To ensure that the developed compressor could be used for these regions a detailed specification was developed in the beginning of the project.

The specification covered various parameters as listed in figure 5.1.

For each parameter detailed sub specifications were formulated and any differences between the market regions highlighted.

Besides technical parameters also legal and standardization requirements were analyzed and formulated, with the aim to ensure a global usability of the compressor.

Specification parameters – fig. 5.1
Process Media
Certification
Area Classification
Inlet Pressure Range
Inlet Temperature Range
Discharge Pressure Maximum
Capacity @ maximum discharge
Capacity @ medium discharge
Capacity @ low discharge
Number of Compression Stages
Number of Compression Heads
Compression Stage-1 Design Pressure Rating
Compression Stage-2 Design Pressure Rating
Crankcase Size
Energy Consumption at Compressor shaft
Compressor driver size
Operating Speed Range
Start Time
Start Pressure
Start Pressure – long term target
Targeted number of start/stops
Ambient Temperature Range
Noise Level
Skid Length maximum
Skid Width maximum
Skid Height maximum
Target lifetime
Target cost
Service interval
Hydraulic Unit
Hydraulic Unit Dimensions
Integration Target
Standards requirements
Certification regions

5.2 Development of compressor components for dual-head capability

The main development activity in the project has covered the development of the 1st stage compressor head and piston rod as well as redesign of all Balance of Plant components (hydraulics and valves) to enable dual-head capability.

Sections below provide a recap of the main results of the development efforts.

5.2.1 Design of 1st stage head for low inlet pressures

A new 1st stage compressor head has been developed as shown in figure 5.2.1.1

Compared to the existing 2nd stage head, the new 1st stage has a greater displacement in order to accommodate the same hydrogen flow despite the lower operating pressures.

The 1st stage head builds on the design principles and experiences from the 2nd stage. However to improve likelihood of a successful design, advanced modelling tools has been developed.

Computational fluid dynamics (CFD) and Finite Element Analysis (FEA) models has been used for simulating flows, stress and temperatures in complex systems – which was exactly what was needed for the development efforts the 1st stage head.

Fig. 5.2.1.1 1st stage compressor head

Flow of both oil, cooling water and hydrogen were to be optimized to ensure high efficiency. For both oil and hydrogen the inflow and outflow to/from the compressor head must be achieved with as little turbulence as possible. For the cooling water the cooling channels were to be designed as small as possible to avoid impacting strength of the components, but whilst still providing sufficient cooling.

Stress is a key parameter in the designing of compression systems. The high pressures re-quires the components to be sufficiently dimensioned with regards to stress and also taking into consideration continuous wear that may impact strength. When adding internal cooling channels close to the high pressure areas, understanding stress becomes even more important.

Temperature is one of the key contributors to wear and greatly affecting efficiency. Under-standing of heat evolvement throughout the compressor system is important for developing an optimal cooling system, that not only reduces the hydrogen gas temperature, but also helps reduce temperature of various wear components.

The developed CFD and FEA models were used to optimize key components in the head, among others:

- **Top plate**
  Placed on top of the diaphragm and with integrated gas inlet and outlet valves. Dimensioning based on the CDF and FEA models to ensure sufficient strength and optimal flow of the gas inlet and outlet. Bolt holes integrated around the outer edge and used to clamp the top plate, middle plate and lower plate together.

- **Middle plate**
  Acts as the bed for placement of the diaphragm and connects with the oil in-let/outlet on the lower plate. Besides of guiding the oil flow the plate also seals of the internal cooling in the lower plate.

- **Lower plate**
  Contains the oil inlet/outlet connected to the piston cylinder. The CDF and FEA models where used to ensure dimensions with sufficient strength, opti-mal oil flow and in particular optimal design.

Fig. 5.1.2.2 below shows a stress simulation for the compressor head. Particular focus on stress in relation to the head, was firstly to ensure sufficient strength of the top and bottom plate, and secondly the flow channels. Simulations was also conducted on heat evolvement in the head to determine the relevant areas for the internal cooling system. Various other simulations were conducted for the other compressor head components.

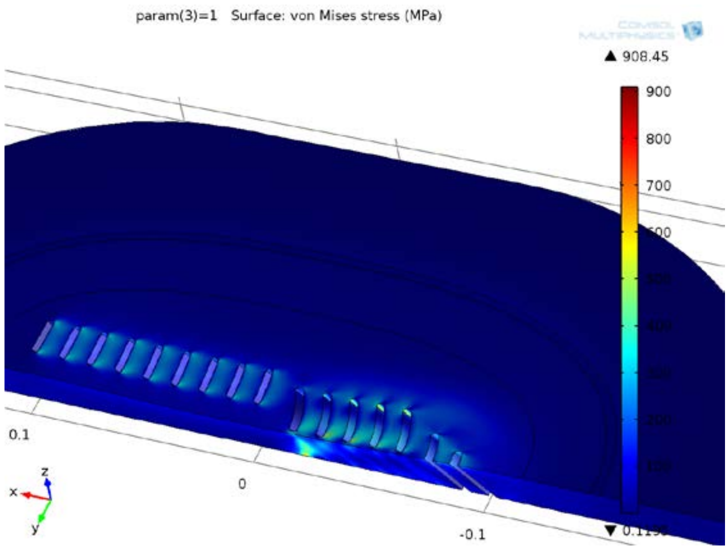

Figure 5.1.2.2 – Stress simulation for compressor head

5.2.2 Design of piston rod and seals

A new piston rod and seal has been designed for the 1st stage compressor head. This has involved and improvement of the existing design from the 2nd stage head (from HyBoost-1).

The piston rod and seal is subject to great stress from the high differential pressure between the crank side and the cylinder side. Also the friction between the piston and seal causes heat generation and wear

Due to the 1st stage operating at lower inlet pressures, generally the heat generation and associated wear is greater than on the 2nd stage. As the piston rod and seals are the weakest part in the compressor, it was necessary to conduct new CFD and FEA stress simulations of an improved design with greater wear resistance and strength.

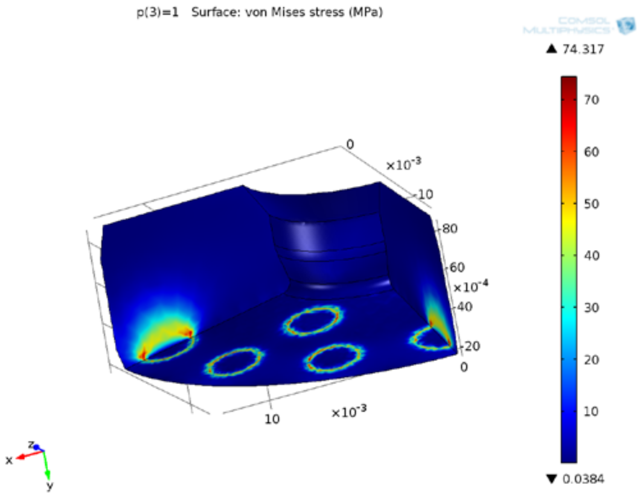

Figure 5.2.2.1 – Stress simulation for piston rod seal

Figure 5.1.4 shows a FEA stress simulation of the piston rod sea house.

A new piston rod seal house design has been developed with cooled lubrication as outlined in figure 5.2.2.2.

The seal housing is the interface between the compressor head assembly and the crankcase. The seal housing also controls the alignment of the hydraulic rod, seal, and bearings, as well as the cooling bushing. It additionally routes the cooling into and back from the packing holder to help cool the rod seal.

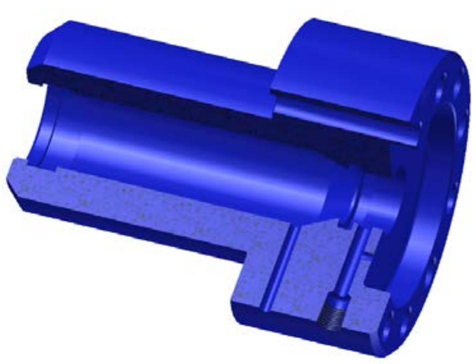
Fig. 5.2.2.2 Piston rod seal house

Coolant is infused behind the seal to ensure sufficient lubrication of the piston during operation and in particular removal of heat. The oil is cooled via a heat exchanger connected to the overall cooling system. Purpose of the heat removal is to reduce the temperature of the seal and thus reduce wear.

The CDF and FEA models where used for the dimensioning to ensure sufficient strength of the seal holder and for designing the oil lubrication channels.

5.2.3 Development of new hydraulics system for dual-head capability

A new hydraulics system has been designed to allow for operation of two heads.

This involved development of a new variable oil pressure system, where the pressure is independent for each head and also independent of the compressor operation (RPM). Traditional hydraulics systems are designed with overflow in order to allow for the flow to be linked with the RPM of the compressor. This typically results in a less efficient oil flow and also a not optimal oil pressure management in each head. The new developed hydraulics system instead is independent of the RPM and oil flow is optimized for each head, avoiding overflow of oil.

A supporting oil management system was also developed, in particular focusing on reducing footprint, to allow for placing the system on top of the compressor power frame.

5.2.4 Development of valve system with dual-head capability

Various valves throughout the compressor has been redesigned for dual-head capability. Also a dedicated effort was conducted on improving the hydraulic relief valve to fit with the new hydraulics system.

On current state-of-the-art mechanical compressors the hydraulic relief valve is used to handle the pressure fluctuations in the hydraulic oil circuit. To high pressures can cause increased stress on the diaphragm and thus increased wear.

The relief valve ensures that peak hydraulic oil pressures are reduced during operation – but this also tends to cause high pitch sounds from the valve. Compared to other noise sources in the compressor system, the high pitch sound is more difficult to contain for the equipment enclosure. Also conventional relief valves are subject to wear due to the fast movement of the springs during operation.

A completely new design and principle for a relief valve was therefore developed.

The new design features a different pressure control approach that manages peaks in the hydraulic oil, rather than “venting” the overpressure. This greatly reduces the noise and allows for a much more precise oil flow that fits the need of the specific head. The new design also have wear surfaces, as the conventional relief valves. The CDF and FEA modelling tools was therefore also applied during design of the pressure relief valve. This helped firstly to ensure a design of sufficient strength, but also to identify surfaces subject to great stress and wear.

5.3 Development of components for integration into HRS

As the aim of HyBoost-2 has been to achieve a compressor integrated into an HRS, various supporting components were to be developed. In HyBoost-1 the compressor was only operated in a laboratory with various supporting facilities and components. For integration into an HRS various aspects of the compressor needs to be integrated with the HRS design, as outlined further in sections below.

5.3.1 Development of compressor control and integration in HRS control

A new control software for the compressor operation has been developed. Previously in the HyBoost-1 project the compressor was only operated in laboratory using a test control system that only allowed for manual operation.

In order to enable integration of the compressor into an HRS a new software package was developed to allow for automatic operation of the compressor. Advanced control principles has been developed to allow for "on-the-fly" optimization of flow and pressure to fit the exact demands during operation. This covers both aspects during fueling and during idling where rebuffer of storage is conducted.

The compressor software was developed as a packaged and then afterwards merged into the overall controls system of the HRS – with the aim to verify workability and conduct fine-tune as part of the test activities.

5.3.2 Compressor cooling and integration with HRS cooling

A new compressor cooling circuit has developed which enables integration with the HRS cooling system. This eliminates the need and costs for a separate dedicated cooling system for the compressor.
The developed cooling circuit interface to the HRS is outlined in figure 5.3.2

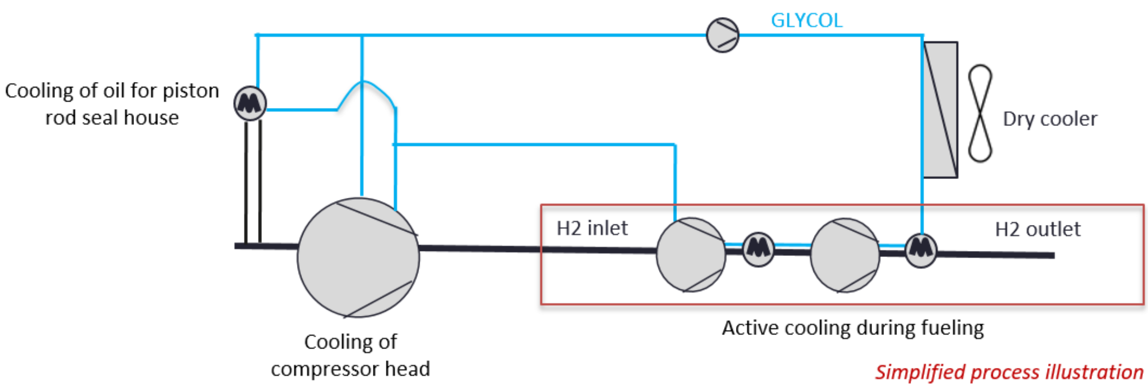

Fig. 5.3.2 Compressor and HRS cooling system overview

The compressor cooling is connected to the glycol based cooling system of the HRS. This covers a small heat exchanger for cooling the oil for the piston rod seal house lubrication. Cooling of the compressor head is directly connected to the glycol system.

The glycol is passing through a dry cooler using ambient air (fans) for cooling. The active cooling during fueling is a separate system with additional cooling compressors, but these also use the glycol to lower the temperature ambient levels, before further cooling.

Overall the cost impact from the compressor cooling is limited to the interface to the glycol system and thus very limited. The heat contribution from the compressor only requires a modest increase of the dry cooler capacity and as this is a standard component the costs associated are limited.

5.3.3 Development of compressor skid for HRS integration

To assemble the various compressor components and ensure that it fits inside the HRS, a new compressor power-frame has been developed – see figure 5.3.2.

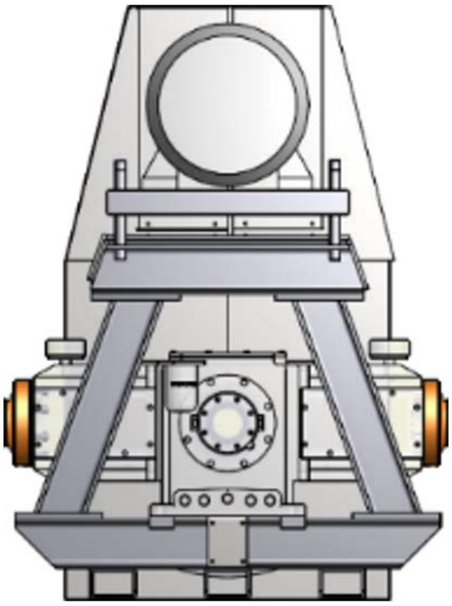

Figure 5.3.3 – Compressor power-frame

The power-frame houses the crank-case, electrical motor and all support balance of plant components.

The compressor heads and rod sealing house are mounted onto the crank-case. The crank-case is a standard from conventi-onal suppliers, however several few design modifications has been made to ensure easy mounting of compressor heads and components.

The electrical motor is sourced from con-ventional suppliers, but with a new mount-ing design on the power-frame that allows for use of electrical motor designs for dif-ferent market regions.

The balance-of-plant system od mounted onto the power-frame. This includes gas valves and pipes, hydraulic system and electrical and control cables.

The main development effort was on the actual power-frame design, where several features was desired. The power-frame is design to house the crank-case and allow for mounting onto a concrete foundation. The power-frame is designed to channel vibrations to the foundation, thereby achieving a more smoot and less noisy opera-tion.

Also the power-frame is designed for placement of the electrical motor on top of the crank-case. This enables a very compact footprint, compared to the typical ap-proach of placing the motor next to the crank-case.

5.4 Compressor prototype construction and tests

5.4.1 Construction of laboratory prototype and integration into HRS

Two compressor prototypes has been constructed in the project. Besides featuring both the existing 2nd stage head and the newly developed 1st stage head, the prototypes also integrates the various other developed components such as balance of plant, compressor skid, cooling circuits and control software.

Originally only one compressor prototype was planned, however in order to advance the schedule a first prototype was constructed and tested in laboratory. This allowed for earlier start of tests and to collect lessons learned that could be used for improving the compressor prototype for integration into an HRS.

Figure 5.4.1.1 shows the laboratory compressor prototype and figure 5.4.1.2 the finalized prototype that was integrated into an HRS.

Figure 5.4.1.1 – Laboratory compressor prototype

Figure 5.4.1.2 – Compressor prototype integrated into HRS

5.4.2 Compressor test

The compressor prototypes have undergone various extensive tests to validate performance and lifetime.

Climate tests have been performed to validate the system capability of operating at cold and hot ambient temperatures. Below are shown test results matrixes for cold and hot tests.

Cold Climate Test Matrix							
	Inlet. Press.	**Gas Inlet Temp.**	**Disch. Press.**	**Disch. Temp.**	**Run Duration**	**Start/Stop Cycles**	**Cycles Achieved**
	[barg]	**[deg C]**	**[barg]**	**[deg C]**	**[h]**		**[MM]**
Part – 1	150	6.4	450	66	6	1	0.144
Part – 2	150	9.9	600	80	8	1	0.168

For *"Part – 1 test"*, head temperature was ambient at start (6.4°C) and then cooling loop was cooled down to – 10°C. For *"Part – 2 test"*, head temperature was -10°C at start and cooling loop kept at -10°C. The test confirmed ability to start at below zero temperatures. Test was only run for few hours, as the compressor head quickly increases in temperature after start.

Hot Climate Test Matrix							
	Inlet. Press.	**Gas Inlet Temp.**	**Disch. Press.**	**Disch. Temp.**	**Run Duration**	**Start/Stop Cycles**	**Cycles Achieved**
	[barg]	**[deg C]**	**[barg]**	**[deg C]**	**[h]**		**[MM]**
Part – 1	175	35	800	125	100	13	3.5
Part – 2	175	28	900	120	100	15	3.0
Part – 3	180	34	810	143	170	1	6.6
Part – 4	200	34	800	143	195	1	7.6
Part – 5	160	29	600	120	70	2	2.5
Part – 6	175	32	810	142	168	6	6.0
Part – 7	185	34	750	130	100	1	3.6
Part – 8	400	40	900	130	50	1	1.2
Part – 9	300	40	900	135	50	3	2.8
Part – 10	400	40	900	135	100	5	2.5

Multiple tests were conducted, where system design was gradually improved, to achieve a discharge gas temperature as low as possible at high ambient. The *"Part – 10"* showed achieving of a low discharge temperature of only 135°C at a gas inlet temperature of 40°C. This level is below the design limits of the system and components, and will also allow operating at even higher ambient temperatures up to 50°C.

Also performance tests were conducted to validate achieving of the target capacity. This showed the expected 50% increase in capacity within the 5-20MPa inlet pressure, at 95MPa outlet pressure.

Majority of test efforts of the compressor focused on achieving of long lifetime whilst having continuous start/stops resembling likely use in field with intense fueling profiles.

Multiple test cycles have been conducted, with continuous design iterations with dismantling and inspection of failed parts and redesigning hereof. This led firstly to achieving of 34 million cycles without part replacements, which is where fatigue curve of the diaphragm flattens, and theoretically allows for unlimited continued operation.

Final test was a combined durability and start/stop test. Total 105 million cycles and 4.000 hours operation with 5.000 start/stops was achieved. The test was conducted in 3 steps, with dismantling and component inspections in each step, but with no change of parts as inspections showed no component issues. This achievement allowed for commencing of the product maturing activities.

Results of the durability tests are outlined in table below.

Final durability and start/stop test							
	Inlet. Press.	**Gas Inlet Temp.**	**Disch. Press.**	**Disch. Temp.**	**Run Duration**	**Start/Stop Cycles**	**Cycles Achieved**
	[barg]	**[deg C]**	**[barg]**	**[deg C]**	**Acc. [h]**		**Acc.[MM]**
Part – 1	150-400	25	450-900	100-130	1000	1700	36MM
Dismantling of compressor – inspection of components – no issues – tests continued							
Part – 2	150-400	30	450-900	100-130	2000	3000	65MM
Dismantling of compressor – inspection of components – no issues – tests continued							
Part – 3	150-400	35	450-900	100-130	4000	5000	105MM
Dismantling of compressor – inspection of components – no issues – tests continued							

5.6 Dissemination of results

Dissemination efforts during the project period has focused on extensive dialogue with market stakeholders of the project partners, in particular customers such as energy companies and car manufacturers.

The aim has been to secure a detailed dialogue on specifications and market requirements during the project execution, and to foster potential sales channels for the following commercialisation of the developed technologies.

Project progress and results have been disseminated on a continuous basis through the Hydrogen Denmark (Brintbranchen) organisation e.g. in meetings and conferences. The partners have also ensured dissemination through international organisations such as the European Fuel Cells & Hydrogen Joint Undertaking, California Hydrogen Fuel Cell Partnership and the US Fuel Cell & Hydrogen Energy Association.

6. Utilization of project results

The participating companies has successfully ensured continued R&D and commercialisation activities of the technologies developed in the HyBoost-2 project.

The HyBoost-2 results on the hydrogen compressor system has successfully been commercialised for the Light Duty Vehicle (LDV) market by Nel Hydrogen (outside of the project) and with new R&D and demonstration efforts ongoing for the Heavy Duyt Vehicle (HDV) market.

Nel Hydrogen introduced a product matured version of the compressor in late 2018 that is now standard in all H2Station®. A line production has been established for the compressor at existing factory in Herning, Denmark. Nel Hydrogen has already secured multiple sales and conducted first installation of the multiple new H2Station® for LDV fueling in Europe, USA and Korea, that features the compressor from HyBoost-2.

To further utilize the compressor system from HyBoost-2 for HDVs, EUDP funding has been secured for a new development project, HyTon, which is to design a new compressor with a daily capacity of 1,5 tons of hydrogen sufficient for fueling of HDVs. The project was commenced in 2019 and will elapse until 2021.

Securing of IPR has been an integrated part of the project and a total of four patent opportunities has been identified and specific patent applications submitted.

Since commencing of the HyBoost-2 project in 2016 the number of average employed persons (as stated in annual final report) at NEL in Denmark has grown from 50 to 85 (2018). At the time of this report issue, NEL employees 105 persons, with an expected conservative outlook of a 10% increase per year going forward, thanks to among others the results of HyBoost-2. With regards to annual revenue of NEL in Denmark this has grown from 44 million DKK in 2016 to 177 million DKK in 2018 with an expected conservative outlook of a 30% increase per year going forward, thanks to among others the results of HyBoost-2. Almost 100% of the revenue generated by NEL in Denmark is export to Europe, USA and Korea.

7. Project conclusion and perspective

HyBoost-2 has successfully managed to further advance the novel and patented compression technology for Hydrogen Refuelling Stations (HRS), developed in the EUDP supported HyBoost-1 project (64014-0556).

HyBoost-2 has developed a new 1st compressor head that enables capturing of hydrogen down to 5MPa inlet, compared to previously only 20MPa. This has enable a doubling of compression capacity achieving a similar capacity as gasoline stations per dispenser hose.

Various other components of the compressor has also been developed, both to allow dual-head operation capability and various supporting components to allow for a full integration into an HRS.

Two full scale compressor prototypes have been constructed and tested, one in laboratory and one where the compressor is integrated into an HRS. The tests validated a lifetime of 100 million compression cycles (4.000 hours) without maintenance and including 5.000 start/stops. Also hot and climate tests have successfully been conducted, respectively up to 45degC and -10degC ambient.

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