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Investigating experimentally the performances of a natural gas reciprocating compressor adapted to pure hydrogen up to 30 MPa

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Abstract. Hydrogen as an energy carrier can be integrated into various value chains, enabling the decarbonization of hard-to-abate processes. Hydrogen storage is necessary to handle the intermittency of renewables. Moreover, it allows hydrogen to be deployed in sectors such as mobility and backup power. Currently, high-pressure vessels are typically used for hydrogen storage. The compression process is required since hydrogen production occurs at lower pressure than storage. This study examines a three-stage reciprocating compressor for natural gas, which is operated with pure hydrogen. The compressor, driven by a 3-kW electric motor, can deliver 30 MPa starting from pressures between 0.3 and 0.8 MPa. The aim is to assess the energy impact of compression on hydrogen production and analyze potential issues such as leakages or contamination that can arise after changing the fluid. The study involves measuring hydrogen flow rates, inlet and outlet pressures, and electric power consumption during the filling of a vessel. The experiment shows a specific power input of 1.2 kW/(Nm3/h), more than 1/3 of the lower heating value, maximum isothermal efficiency of 21% and maximum isentropic efficiency of 34%. The optimal compression ratio is found to be between 25 and 30. Based on the few data available in literature, the performances do not reach state-of-art levels of 55-80% isentropic efficiency. However, the device was optimized for the compression of natural gas, and the scope of this study was to use it with fewer possible modifications.

1. Introduction

Hydrogen as an energy carrier can be integrated in multiple value chains with minimal disruption and can enable the decarbonization of hard-to-abate processes. Hydrogen compressors are crucial for increasing the energy density of hydrogen. Commercial proton exchange membrane water electrolysis (PEMEL) today operates at hydrogen outlet pressures of 3–4 MPa [1, 2] and this result in a very low energy density of 0.3 MJ/l. The energy density is a key factor for its storage and delivery for both stationary and automotive applications [3]. There are many storage technologies under study such as liquefaction, gas compression and solid-state storage, however for medium- and small-scale applications, gas compression remains the most promising one [4].

When dealing with gas compressor a distinction is made between rotary and positive displacement compressors. In a rotary compressor, energy is exchanged between a continuous flow of working fluid and a set of blades called impellers. The centrifugal compressor is a common example of a rotodynamic compressor. In a positive displacement system, the volume of the working chamber is cyclically changed by the mechanical movement of a displacement member, usually a piston or rotor. The fluid in the chamber is compressed as the volume decreases until the desired pressure has been reached [5]. Reciprocating compressor falls in this second category.

Positive displacement category held the larger share in the compressor market thanks to higher efficiency, lower operating cost, higher pressure ratio for a relatively small size, and suitability for wide-ranging application areas [6]. Along with those more traditional mechanical compression technologies, there are also electrochemical compression technologies that uses electrochemical reactions to compress hydrogen gas and typically involves the use of proton exchange membrane (PEM) cells like the one found in fuel cells. This is a promising technology however it is still in an early research stage [7]. In this context, it is interesting to understand how well the established reciprocating compressor technology can be transferred from the compression of natural gas to the compression of hydrogen. This can help solve a research gap and reduce the time needed to have solutions available to the market. Moreover, it is interesting to see how the already installed compressor can be employed in case of a conversion of the natural gas grid to a hydrogen one.

This work characterizes a natural gas compressor adapted for hydrogen in terms of overall performances. The device consists in a 3-stage reciprocating compressor driven by a 3 kW electric motor that can deliver hydrogen at 30 MPa starting from a pressure between 0.3 and 0.8 MPa. After compression, the hydrogen is stored in a vessel that progressively fill up building up pressure. The preliminary investigation shows that the lubricating oil from the pistons contaminates the compressed hydrogen, therefore a filtering section is included at the outlet of the compressor. This is the only modification required to be able to operate the compressor with pure hydrogen.

The goal of the work is the evaluation of the impact of the compressor in the hydrogen value chain. Therefore, in the study the compressor is treated as a system rather than going in details analyzing each of its component. The results report the specific energy needed for the compression, which is the electric energy consumed divided by the flow rate processed, and different efficiencies. The specific energy is particularly useful to optimize the value chain of hydrogen. The main conclusion is that the existing reciprocating compressor adapted to work with hydrogen can be a viable option in its usable range. Following research will compare the operation with natural gas with respect to the operation with hydrogen. This will help understand better the influence on performance that results from the change in fluid processed. Moreover, this paper provides real experimental efficiency data of a hydrogen compressor, of which there is very limited literature available [8]. Among the few available data, Sdanghi et al. [3] and Tahan et al. [9] indicates isentropic efficiencies in the range 55-80%.

The paper is structured as follow. Section 2 provides a description of the experimental apparatus used to characterize the compressor with detailed information on the instrument employed. The methods used to perform the test and analyze the result are presented in Section 3, where the performance indicators used are defined. In Section 4, test results are presented and discussed. Finally in Section 5 some conclusions on the impact of the compression in the hydrogen value chain are drawn based on the results obtained.

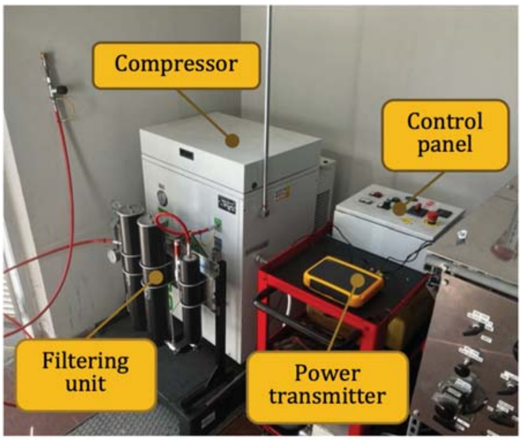

Figure 2. Experimental setup featuring compressor, control panel, filtering unit and power quality logger.

2. Experimental setup and procedure

This section presents the experimental apparatus employed in the characterization of the compressor. The setup is installed in the Laboratory of Energy Conversion and Storage (LabX) of the Department of Energy of Politecnico di Milano. The relevant parts of the setup are shown in Figure 2, while a schematic representation showing the interconnections between the devices is reported in Figure 1.

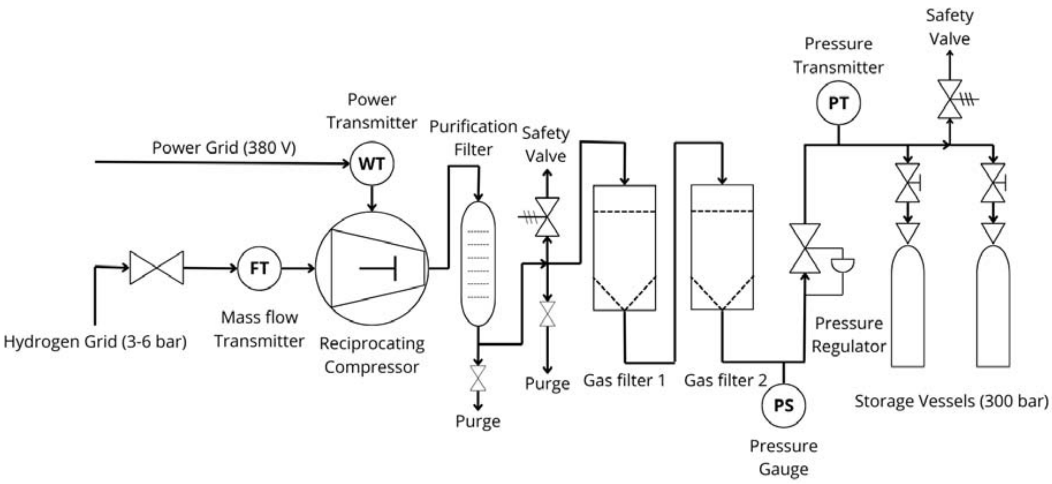

Figure 1. Piping and Instrumentation diagram of experimental setup.

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Table 2. Operating conditions maintained during tests. Consistent with ISO 1217:2009 norm.

Parameter	Value	Unit
Ambient temperature	WT	°C
Fluid	H2 (Grade 5.0)	-
Inlet pressure	0.3	MPa
Voltage supply	380	V

The compressor is a three-stage reciprocating compressor. The pistons are driven by a three-phase 3 kW electric engine through a crankshaft. The compressor can deliver gases at pressure up to 30 MPa. The heat dissipation and the heat and provide intercooling between stages is provided by an air-cooling system. The compressor features his own control panel which monitors the direction of rotation of the electric engine, provide the electric power to the device, and allow to start and stop the compressor. It also includes an emergency button to abruptly stop the compressor in case any issue occurs. Lastly, the control panel is also equipped with an hour meter to monitor the running time and plan the maintenance accordingly.

The compressor needs to be supplied with hydrogen between 0.3 MPa and 0.8 MPa. This is provided by the centralized hydrogen line of the laboratory which is equipped with a manual pressure regulator. The hydrogen flowrate is measured using a Bronkhorst® IN-flow mass flow meter (FT). The compressor performances evaluation also requires monitoring the electric consumption during operation. This measurement is performed with the Fluke® 1748 three-phase power quality logger (WT). The instrument measures the voltage and current of each phase. The voltage measurements require a connection between the instrument and the electric terminal inside the compressor control panel. The current measurements use current clamps clamped around the electrical conductors that enter the control panel. Lastly, a Gems 3100 Series gauge pressure transducer measures the outlet pressure. This sensor measure pressure between 0 MPa and 40 MPa and output a voltage between 0V and 5V. This voltage is then measured by an Arduino Uno R4 and converted into digital value. The measurements from mass flow meter, power quality logger and Arduino are all received in real-time by a laptop where a program developed in LabVIEW® display data and log them. The main parameters of the instruments employed in the setup are summarized in Table 1.

A preliminary investigation reveals that the gas is contaminated by the lubricating oil during the compression. This oil creates two main issues: (i) it accumulates in the pressurized vessels used to store the compressed hydrogen and (ii) it contaminates the devices that use the compressed hydrogen afterward. Since many of the devices that uses hydrogen in the laboratory are very sensitive to contaminants (e.g. fuel cells), a filtering unit is included in correspondence

Table 1. Datasheet of instruments employed in experimental setup to perform measurements. Rd stands for read value, FS stand for full scale.

Measurement	ID	Instrument	Range	Accuracy
Current	WT	FLUKE 1748	0.01-10.00 A	±1.0%Rd ±0.3%FS
Voltage	WT	FLUKE 1748	0.1-600.0 V	±1.0%Rd ±0.5%FS
Mass flow rate	FT	Bronkhorst IN-flow F-113AI	0.2-30 Nm^3/h	±0.5%Rd ±0.1%FS
Outlet pressure	PT	Gems 3100	0-40 MPa	0.25%FS

to the outlet of the compressor. After the filter, a valve allows the disconnection and replacement of the pressurized vessel.

The operating conditions maintained during the operations are reported in Table 2. The tests are performed filling the vessel up to 30 MPa. The inlet hydrogen pressure is 0.3 MPa and the initial pressure of the vessel is 0.8 MPa.

3. Measurements post-processing

The data obtained with the experimental apparatus are then analyzed with MATLAB®. The post-processing aims to assess the measurements uncertainties and calculate useful derived quantity to assess the performances of the compressor.

The uncertainties are calculated following the indication from the "An introduction to error analysis" book [10]. For each direct measurement the uncertainty is provided by the datasheet of the instruments used to take the measure. The value used are the ones reported in Table 1. For the derived quantities, the uncertainties are calculated following the general formula for the error propagation with independent random errors. A derived quantity, y, can be expressed as a function of constants and direct measurements:

$$y = f(x_1, x_2, \dots, x_n) \tag{1}$$

where $x_1, \dots, x_n$ are the direct measurements. From this expression it is then possible to calculate the uncertainty of the derived quantity, δy, as:

$$\delta y = \sqrt{\sum \delta y_n^2} \tag{2}$$

where δy_n is the uncertainty of y related to the uncertainty of the direct measurement x_n and is calculated as:

$$\delta y_n = \frac{\partial f}{\partial x_n} \delta x_n \tag{3}$$

where δx_n is the uncertainty of the direct measurement n. This value is provided by the datasheet of the instrument used and can be found in Table 1.

The first indicator considered is the *specific power input,* w_{sp}, as suggested by the ISO 1217:2009 norm. This parameter is defined as:

$$w_{sp} = \frac{W_{el}}{\dot{V}} \tag{4}$$

where W_{el} is the packaged compressor electric power input, including the power required by any ancillaries and auxiliaries, and $\dot{V}$ is the standard volume flowrate. The value obtained with this definition can be directly compared against the heating value of hydrogen. This indicator is useful during the assessments of the hydrogen value chain. Transport or storage of energy in form of hydrogen requires several steps. The hydrogen needs to be produced, compressed, and converted back to useful energy. Each of these steps requires energy. To assess the quality of each of these processes in a comparable way, it is useful to normalize their consumption against the energy transported which is the fuel chemical energy. In case of compression this is measured with the specific power input.

The other indicators used are the *isentropic efficiency,* η_{isoS}, and the *isothermal efficiency,* η_{isoT}. The general definition for these indicators is:

$$\eta = \frac{W_{id}}{W_{el}} \tag{5}$$

where W_{el} is the packaged compressor electric power input and W_{id} is the theoretical ideal power required to compress the gas.

The difference between the two efficiencies is in the choice of the ideal process, and thus in the definition of the W_{id} term. The isentropic efficiency considers, the theoretical power required for an ideal adiabatic compression process, while the isothermal efficiency consider the ideal isothermal compression process [5].

The ideal work in the isentropic case, W_{isoS}, is defined as:

$$W_{isoS} = \dot{m}\frac{\gamma}{\gamma - 1}\left(\beta^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{6}$$

whereas in isothermal case (W_{isoT}) is defined as:

$$W_{isoT} = \dot{m}\ln(\beta) \tag{7}$$

where γ is the *heat capacity ratio* and β is the *compression ratio* defined as:

$$\beta = \frac{P_{out}}{P_{in}}. \tag{8}$$

4. Results and discussion

In this section the results of the experimental campaign are reported, starting from direct measures, and then proceeding with the derived quantities described in Section 3. The graphs are represented as a function of the *compression ratio* (β) defined before. The compression ratio is the dimensionless representation of the outlet pressure and is therefore useful to obtain generalized results thanks to the similitude theory.

Figure 3 represents the direct measurement of flowrate (Figure 3a) and power (Figure 3b) as a function of the compression ratio. Up to compression ratio of 40, the flow rate remains constant around 4.85 Nm^3/h and the power decrease less than linearly. Increasing further the compression ratio, the flowrate starts decreasing linearly at about 0.044 Nm^3/h per unit of compression ratio, while the power start increasing less than linearly. At compression ratio 90 the flowrate stabilizes around 2.72 Nm^3/h, and the power reaches its maximum and stabilize at 3.03±0.033 kW. Excluding the very start-up phase at the lower end of the compression ratio, the maximum flow rate of 4.90±0.025 Nm^3/h is achieved for compression ratio of 40 and the point correspond to the minimum of the power of 2.69±0.030 kW.

The results that follows are related to the derived quantities. The specific power input is the first of them and is represented in Figure 4. In the graph, the specific power input is represented as a function of the compression ratio. The specific power input required to compress hydrogen from 0.3 MPa to 30 MPa (i.e. compression ratio of 100) is 1.12±0.014 $kW/(Nm^3/h)$. This is more than 1/3 of the lower heating value (LHV) of hydrogen which is 3.00 kWh/Nm^3. It is possible to observe that the specific power input is strongly reduced by decreasing the compression ratio from 100 down to 40. Decreasing further below 40, the specific power input reaches 0.57 $kW/(Nm^3/h)$ and stay constant for lower compression ratios. By applying the similitude theory, we can expect that, if the outlet pressure is fixed at 30 MPa, having an inlet pressure higher than 0.75 MPa would reduce the impact of the compression work to about 1/6 of the hydrogen lower heating value. This inlet pressures are reasonable if we imagine that the hydrogen would come

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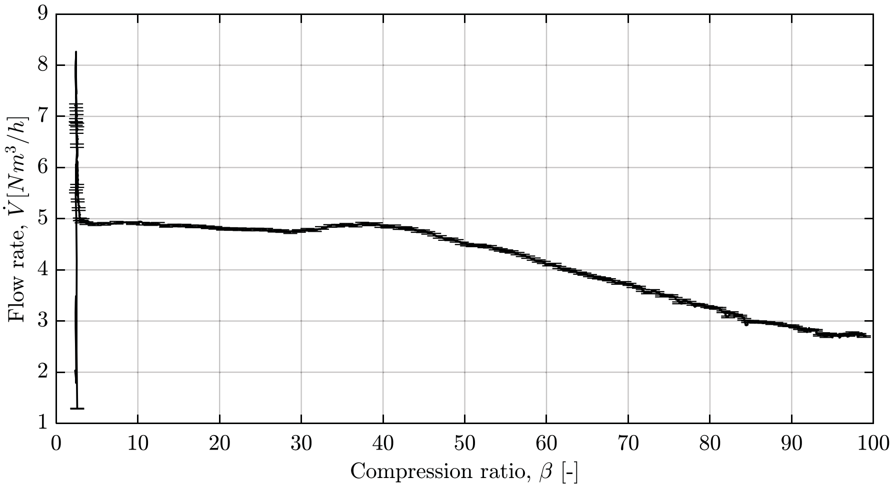
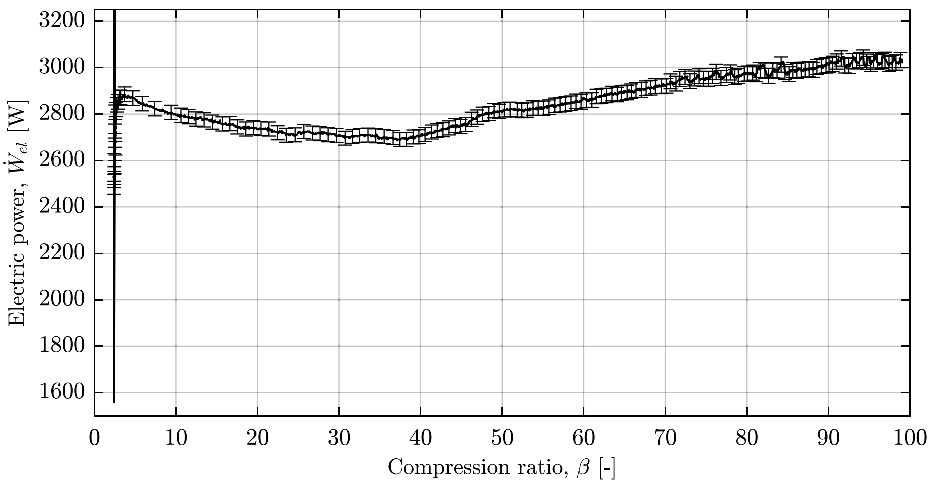
from an electrolyzer. As reported in section 1, commercial proton exchange membrane water electrolysis (PEMEL) today operates at hydrogen outlet pressures of 3–4 MPa with study experimenting also with even higher pressures [1, 2].



(a) Flow rate as a function of compression ratio



(b) Electric power as a function of compression ratio

Figure 3. Evolution of the direct measurements as a function of compressor ratio. Outlet pressure follow from filling the vessel downstream. Inlet pressure is kept at 0.3MPa

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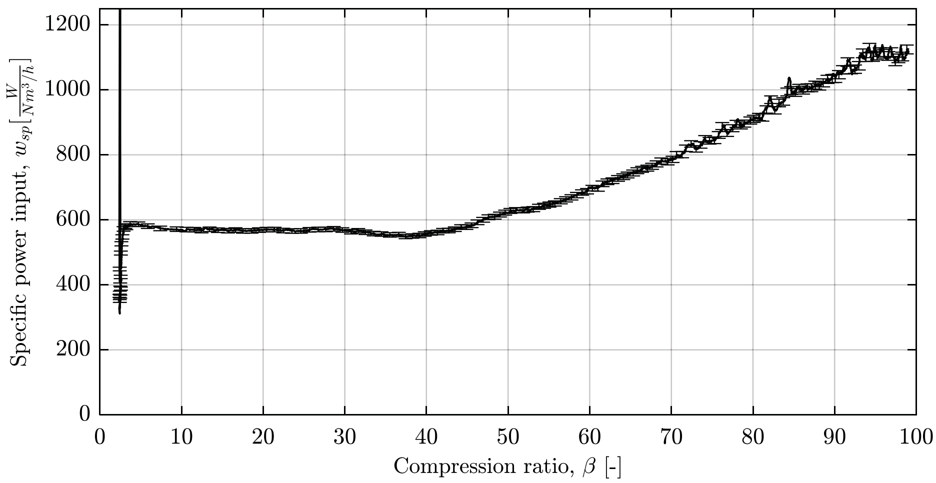
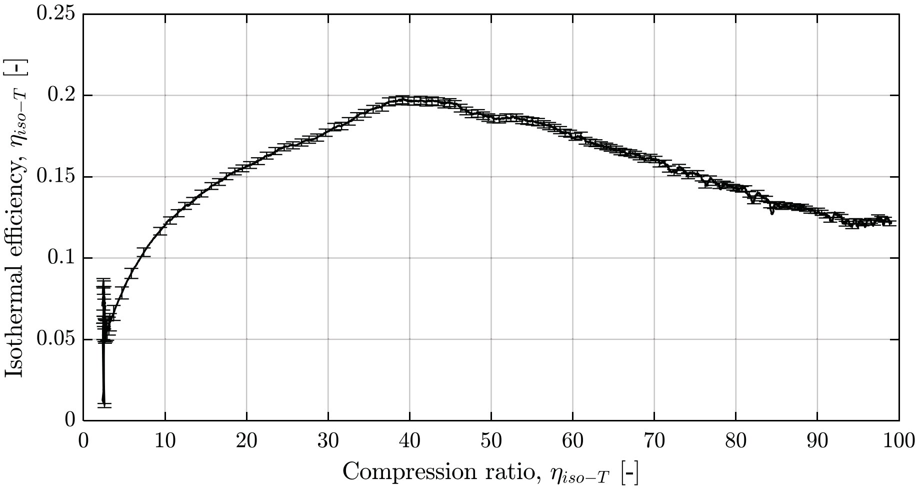


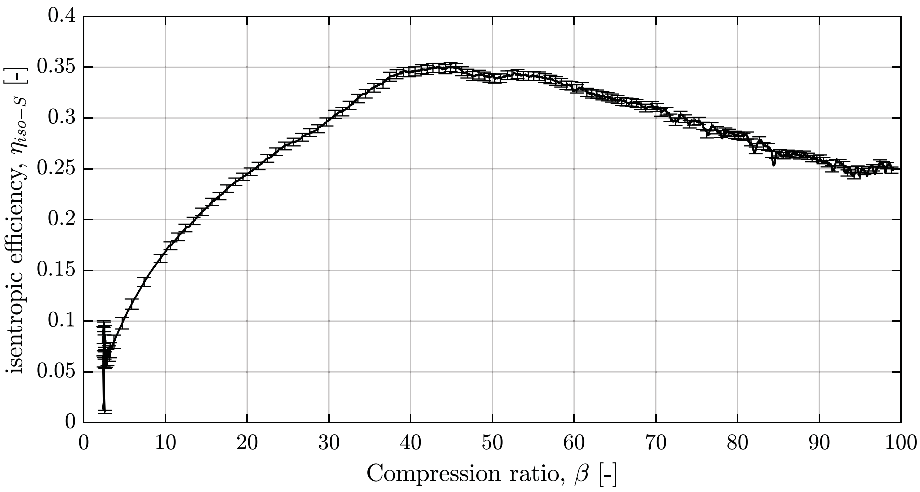
Figure 4. Evolution of specific power input needed for compression as a function of outlet pressure and compression ratio. Outlet pressure follow from filling vessel downstream. Inlet pressure is kept at 0.3 MPa

The results that follows are related to the derived quantities. The specific power input is the first of them and is represented in Figure 4. In the graph, the specific power input is represented as a function of the compression ratio. The specific power input required to compress hydrogen from 0.3 MPa to 30 MPa (i.e. compression ratio of 100) is 1.12±0.014 kW/(Nm^3/h). This is more than 1/3 of the lower heating value (LHV) of hydrogen which is 3.00 kWh/Nm^3. It is possible to observe that the specific power input is strongly reduced by decreasing the compression ratio from 100 down to 40. Decreasing further below 40, the specific power input reaches 0.57 kW/(Nm^3/h) and stay constant for lower compression ratios. By applying the similitude theory, we can expect that, if the outlet pressure is fixed at 30 MPa, having an inlet pressure higher than 0.75 MPa would reduce the impact of the compression work to about 1/6 of the hydrogen lower heating value. This inlet pressures are reasonable if we imagine that the hydrogen would come from an electrolyzer. As reported in section 1, commercial proton exchange membrane water electrolysis (PEMEL) today operates at hydrogen outlet pressures of 3–4 MPa with study experimenting also with even higher pressures [1, 2].

The efficiency is the next indicator that was considered. Figure 5 represents the trends of both the isentropic efficiency and the isothermal efficiency varying the outlet pressure while keeping the inlet pressure constant. In the graphs it is possible to see that there is an optimum compression ratio of 40 that maximizes the efficiency of this compressor at 19.7±0.25% isothermal efficiency and 35.0±0.45%. Below compression ratio 40 there is a steep decrease in performances, especially for the isentropic efficiency. In the range between 40 and 45 the efficiencies stay almost constant, then start decreasing. As reported in section 1, the reported efficiencies are in the range 55-80%. The efficiency that we obtain in the tests are lower, however the small scale of the device is expected to have an important impact on the device performances. Moreover, the performances could also be improved optimizing the cooling air flow rate. The lower density of hydrogen with respect to natural gas, combined with the fact that volumetric machines maintain the same volumetric flowrate changing the fluid, means that the required cooling power is decreased switching the fluid. Lastly, the filtering unit included to achieve the required hydrogen purity also impact the performances by introducing additional pressure losses at discharge.



(a) Isothermal efficiency vs compression ratio



(b) Isentropic efficiency vs compression ratio

Figure 5. Evolution of compression efficiency as a function of compression ratio. Outlet pressure follow from filling vessel downstream. Inlet pressure is kept at 0.3 MPa.

5. Conclusions

In this work the performances of a 3-stage reciprocating compressor have been characterized, focusing on the evaluation of the impact that the compression has in the hydrogen value chain. For this reason, the compressor has been considered as a system without going into details analyzing the compression cycle. The conclusions are as follow.

- The specific power input required by this compressor to compress hydrogen from 0.3 MPa to 30 MPa is 1.2 kW/(Nm^3/h) which is more than 1/3 of the lower heating value (LHV) of hydrogen. This figure can be reduced to about 1/6 when the compression ratio is decreased below 30.

- The compressor shows an optimal compression ratio between 25 and 30 when operated with pure hydrogen where the compressor achieves 21% isothermal efficiency and 34% isentropic efficiency. This corresponds to a compression ratio per stage of around 3. This compression ratio could be adequate to a scenario where the hydrogen is available at 1-3 MPa like from conventional PEM electrolyzers
- The compressor worked with pure hydrogen without major issues. The main issue is the contamination of the compressed hydrogen due to the lubricating oil of the piston. This required the addition of a filtering unit due to the high purity is needed.
- In literature there is a lack of data concerning hydrogen compressor performances, therefore it is difficult to find relevant comparisons. Based on the few data available, the performances do not reach state-of-art levels of 55-80% isentropic efficiency. However, the device was optimized for the compression of natural gas, and the scope of this study was to use it with fewer possible modifications.
- There are many improvements that could be adopted to increase the performances of the device:
    - bigger scale to decrease the impact of dead-volumes, clearances and roughness
    - optimization of cooling-air flowrate to reduce the fan consumption
    - oil-free solutions to remove the pressure loss associated to the filtering unit

The next steps will be the comparison of the performances when the compressor is operated with pure hydrogen or with natural gas.

Acknowledgments

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