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HYDROGEN HYDRAULIC COMPRESSION SYSTEM FOR REFUELLING STATIONS

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The article investigates the properties and potential of compressed hydrogen as one of the most promising energy carriers in order to facilitate the development of energy storage capabilities and lay down a stable foundation for the future of a sustainable energy sector. The study considers the use of hydrogen, compressed at high pressure from 50 MPa to 100 MPa, at refuelling stations to supply electric cars. The technical properties of modern hydraulic compressors used for hydrogen accumulation in high pressure buffer containers are considered. The study shows that the design of hydraulic compressors in terms of their technical characteristics optimally corresponds to the primary requirements for their use as booster compressors at refuelling stations. The authors conclude with the proposal of an enhanced design of the hydraulic compressor with the use of fluid flow counters in a control system of a hydrogen compression cycle. The proposed technical solution provides for continuous monitoring of the hydrogen compression process that increases the reliability of control system operation.

Keywords: *Energy storage, fluid flow counters, hydrogen, high pressure, hydraulic compressors, refuelling stations.*

1. INTRODUCTION

Currently, European countries are focused on finding the ways of increasing the share of hydrogen energy in their energy balance, driven by the desire to reduce consumption and dependency on fossil fuels. Hydrogen has the potential of making a significant contribution to the three most important tasks concerning the energy use: to achieve sustainable economic development of the European Union, reduce greenhouse gas emissions and improve air quality [1], [2].

In recent years, the use of hydrogen energy in transport and the concept of a hydrogen economy have benefited from a

new wave of strong political support. At the same time, rapidly evolving technologies have increased the feasibility of using hydrogen as a driver for the future carbon-neutral energy system. At the heart of this initiative, there is the desire for energy security and independence. At the same time, the European Union has set an ambitious goal to become the first climate neutral continent by 2050, which is in line with the guidelines of the European Commission [3].

John Moore, the CEO of Bloomberg New Energy Finance (BNEF), at the Asian Clean Energy Summit on 30 October 2021 in Singapore made a prediction that by 2030, green-hydrogen with the price of just over $2/kg would start competing with coal and natural gas as an energy carrier in steel production, and by 2050, at $1/kg it would become more profitable than gas in the world markets and compete with the cheapest coal, keeping CO_2 emission at zero. In his opinion, due to hydrogen there will be a kind of final electrification of the world industry [4].

In the real-life environment, hydrogen production can be organised by using a wide range of technologies. Depending on the production method, hydrogen is conventionally labelled green, blue, pink and grey, and specialised terms - safe, sustainable, low-carbon and pure - are also used [5]. Hydrogen, the most widely spread element in the universe, on Earth is found mostly in a bound state. However, the technical capability to produce it by decomposing water with an electric current makes it possible to create and store the reserves of this gas, which has a high energy density and is considered to be an ideal fuel. The utilisation of renewable energy sources, which are practically inexhaustible, for hydrogen generation allows establishing a continuous, sustainable, ecologically clean energy production cycle. Thus, "green" hydrogen is one of the most promising approaches to future energy storage.

Green hydrogen is considered to be the most environmentally friendly and will be an important part of the future 100% sustainable energy system [6]. In the production of green hydrogen, the main emphasis is on the use of wind and solar energy. As a result, a process chain for the production of hydrogen is created by electrolysis of water without emission of carbon dioxide into the atmosphere. Thus, the process of water electrolysis can potentially be carbon free if renewable or nuclear electricity is used [7], [8].

Overall, the development of efficient, cost-effective, competitive and safe technologies for the production and use of hydrogen is the main area of research for the future hydrogen energy industry. The conversion of hydrogen energy into electric current without burning it makes it possible to use this energy source to power the electric vehicles. Currently, there are already examples of successful implementation of hydrogen technology for cars and trucks.[1,2]

2. PROPERTIES OF COMPRESSED HYDROGEN

In general, the cost of hydrogen is determined by the energy cost of its production, but for its widespread use in stationary and mobile systems, a number of issues relating to its storage and transportation should also be addressed [7]. Transportation of gaseous hydrogen is a very expensive operation, because hydrogen density is low, about 0.09 kg/m^3 under standard conditions of temperature and pressure [9]. The density

[1] "Volvo AB and Daimler Trucks team up in a hydrogen fuel cell joint venture" (link).
[2] Toyota Mirai 2022 edition (link).

of hydrogen should be increased by compression and accumulated in a reservoir for storage and transportation to its ultimate use location.

The research results presented in [10], [11] allow us to estimate the influence of the compression process on the change of energy properties of hydrogen. Figures 1–3 show how the energy density (kWh/L), stored in compressed hydrogen, depends on temperature and pressure. Analysis of the curves in the temperature range from 20 °C to 80 °C shows that the hydrogen density increases exponentially with increasing pressure and tends to decrease with increasing temperature.

The graphs clearly show that as the pressure increases, the energy density of hydrogen increases almost linearly only up to 80 MPa. A further increase in pressure is not accompanied by an adequate increase in energy density and is impractical. This increases the cost of the equipment used to compress hydrogen, while the performance of the vehicle is not significantly improved.

Derived curves shown in Figs. 1–3 enable us to estimate weight and energy density of compressed hydrogen contained in a typical 145-litre Toyota Mirai[2] tank with 70 MPa and 20 °C. In this case, energy density is 1.28 kW/L and, consequently, the value of hydrogen storage is equal to 185.6, kWh and gas weight is 5.6 kg.

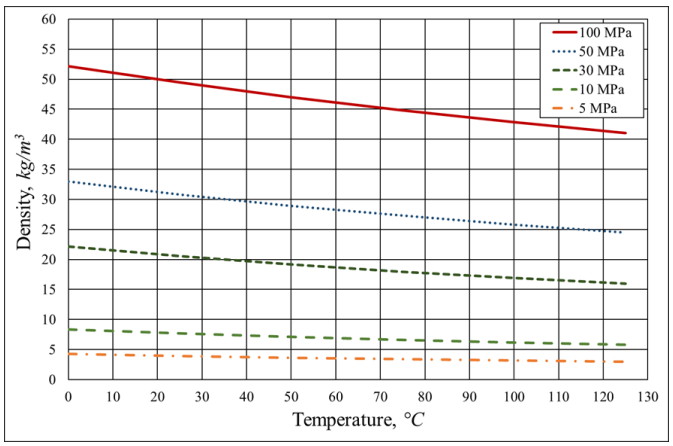


Fig. 1. Hydrogen density as a function of temperature at pressure from 5 MPa to 100 MPa.

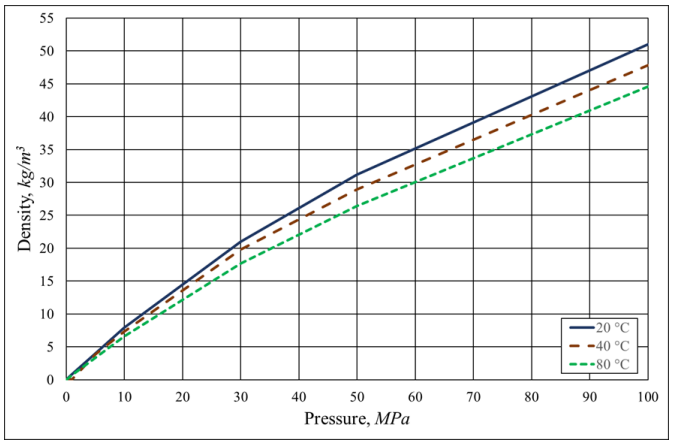


Fig. 2. Hydrogen density as a function of pressure in the interval of temperature from 20 °C to 80 °C.

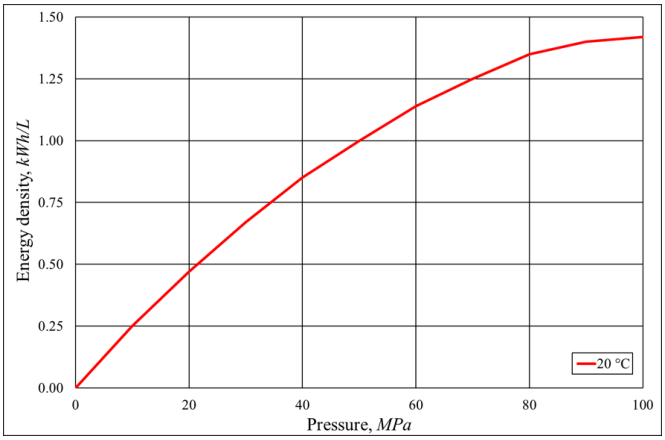


Fig. 3. Energy density of compressed hydrogen as a function of pressure at temperature of 20 ºC.

Pressurised storage of gases, including hydrogen, is a rather mature technology. However, the use of hydrogen tanks in vehicles coupled with the challenge of using very high pressures, requires strict regulations backed up by safety and performance studies.

3. USE OF COMPRESSED HYDROGEN AT REFUELLING STATIONS

In order to use hydrogen at refuelling stations, the necessary infrastructure must be in place to store and prepare the hydrogen for injection into the vehicle fuel tank. For this purpose, hydrogen pressurised at 50 MPa to 100 MPa is used. Accordingly, refuelling stations must be provided with the appropriate equipment, which should only be operated by specially trained personnel [12].

However, due to leakages, the ability to store hydrogen at these high pressures for a long time is limited. Respectively, booster compressor capacities and buffer tanks for high pressure hydrogen must be installed at refuelling stations [13].

Compressed hydrogen is transported by road transport in containerised hydrogen tubes. For example, Linde[3] – a leading industrial gas and engineering company, for this purpose uses trailers shown in Fig. 4.

In practice, large trailers with tank pressures of 25 MPa or less, per tube, with a total hydrogen weight of 560 kg are used for long-term storage and transport; one of its examples is shown in Fig. 5.



Fig. 4. Containerised hydrogen tubes mounted on a trailer for the transport of hydrogen in central Europe (Co. Linde) [14].

[3] Linde Engineering. High-performance hydrogen refuelling technologies. (link).



Fig. 5. Example of a large trailer with tank pressure of 25 MPa, per tube, with a total weight of 560 kg of hydrogen [15].

Articles [7], [16] review different contemporary technologies of hydrogen compression, their working principles, advantages and limitations. It should be noted that, from a wide variety of compressors, the ones with a liquid piston have the lowest energy consumption, as only this technology is able to provide a quasi-isothermal compression process.

The liquid piston is not a new concept, as the earliest known application dates back to 1906. This solution was used in an internal combustion engine for pumping water, known as the Humphrey pump [17]. The Humphrey pump followed the Atkinson cycle and demonstrated efficiencies of between 5 % and 10 % [18].

The liquid piston gas compression concept uses a column of liquid to directly compress gas in a fixed volume chamber. The use of a liquid piston eliminates gas leakage from the compression chamber and eliminates the friction of the mechanical sliding seals present in the cylinders of mechanical compressors.

The use of liquid as a piston provides for a significant increase in efficiency of gas compression. Using a simplified model, it has been demonstrated that this concept can increase the compression efficiency from 70 % to over 83 % [19].

It should be pointed out that the gas compression process is accompanied by high heat generation and the temperature of the gas has an effect on the working fluid. In fact, the fluid and the gas are compressed together, but since the fluid has a higher density and a higher heat capacity, the heat generated during compression is effectively absorbed by the fluid and the surrounding walls of the compression chamber.

Once the compression cycle is complete, the heated fluid is moved from the compression chamber to the heat exchanger, where it is cooled. As a result, hydraulic compressors have an advantage over reciprocating compressors in terms of cooling, as there is no need for external heat exchangers on the compression chambers. This reduces the weight of the compressor and the cost of the entire system [7].

Hydrogen compression technology using a hydraulic compressor has been successfully implemented in Linde appliances, which offers fully integrated systems for use in booster compressor stations. For example, the Type IC50/60 Ionic Compressor, with a connected load of 186 kW, produces up to 56 kg/h of hydrogen compressed to 50 MPa and pumps it into a buffer tank. The unit can be operated at ambient operating temperatures of -20 °C / +40 °C, and the inlet pressure to the system can vary from 0.6 MPa to 20 MPa.[4]

4. ALTERNATIVE DESIGN OF HYDRAULIC COMPRESSOR

A schematic diagram of a refuelling station using hydrogen at inlet pressure from 0.6 up to 25 MPa, either brought by trailer or generated by electrolysis at the station

[4] IC50/60 Ionic Compressor. Compressor module for gaseous hydrogen refuelling station, datasheet. Linde Engineering (link).

itself, is shown in Fig. 6. The proposed concept is especially attractive when combined with the use of green hydrogen produced by electrolysis, fed from wind turbines, solar panels or the electricity grid. Using the booster hydraulic compressor, the low-pressure hydrogen is raised to the required 70 MPa for cars and 35 MPa for trucks and pumped into the buffer storage tanks. The high-pressure hydrogen is then filled into the vehicle tanks via a dispenser.

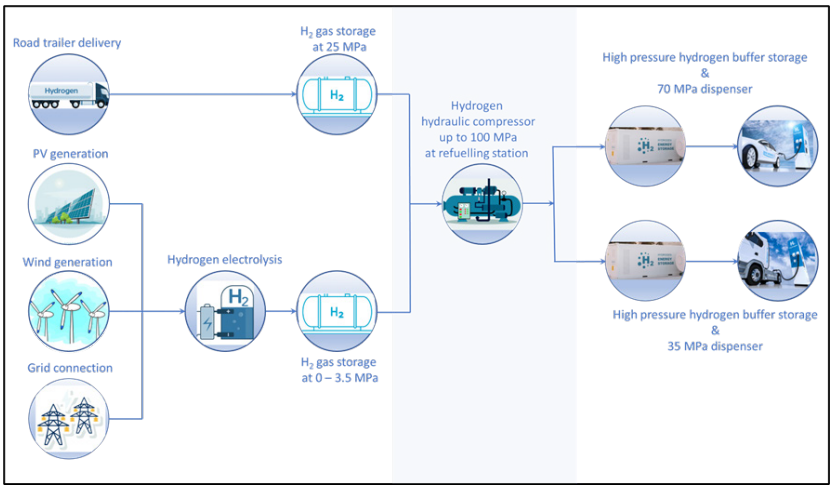


Fig. 6. Schematic diagram of the delivery, storage and preparation of compressed high-pressure hydrogen for use in refuelling stations.

The authors developed an alternative solution of hydraulic compressor design, whose structural scheme is shown in Fig. 7 [20]. It is assumed that the device is designed for use as a booster compressor in a refuelling station system that uses hydrogen brought in by a truck in tubes or produced locally by electrolysis of water in limited quantities. For example, an Enapter electrolyser can produce up to 500 L/h or 1.0785 kg H_2 at 20 °C and 3.5 MPa.[5]

The proposed device contains a tank H_2 for low pressure hydrogen storage, two operating cylinders V_1 and V_2 of the first compression stage, an operating cylinder V_3 of the second compression stage and a buffer cylinder V_4 for high pressure hydrogen storage, connected to each other by pipelines.

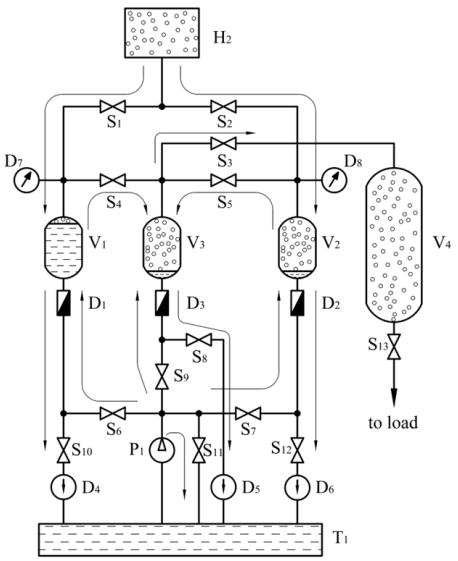


Fig. 7. Schematic diagram of the connection between the working cylinders and the hydrogen tanks in the hydraulic compressor.

[5] AEM Electrolyser EL 4.0, datasheet. Enapter (link).

Hydraulic compression system consists of a tank T_1 with working fluid and high-pressure liquid transfer pump P_1, connected by pipelines to the operating cylinders V_1, V_2 and V_3. The level of working fluid in the cylinders and, consequently, the gas compression ratio, is controlled by fluid flow counters D_1, D_2, D_3. The flows of hydrogen and working fluid are switched by the servo-controlled valves S_1 to S_{13}. The optical fluid flow control sensors D_4 – D_6 help control the flow of working fluid in pipelines, while cylinders V_1, V_2 and V_3 are filled with hydrogen. The pressure level in the pipelines is controlled by pressure gauge D_7, D_8.

The arrows in the diagram (Fig. 7) show the direction of flow of working fluid from tank T_1 through pump P_1 and the direction of hydrogen flow from storage H_2 to buffer cylinder V_4 after performing a compression cycle in operating cylinders V_1–V_3.

The valves are switched on according to a specified algorithm, which implements the following cycle of hydraulic compressor operation. At the initial state, all valves are closed, and the pump is switched off. The first step is to open the valve, e.g., S_2, through which hydrogen from tank H_2 enters operating cylinder V_2 and then the S_2 valve is closed.

The next step is to switch on the pump P_1 and open valve S_7, through which working fluid from the tank T_1 flows into the operating cylinder V_2 by pipeline and through the fluid flow counter D_3. The amount of working fluid entering the operating cylinder V_2 is measured by fluid flow counter D_3 and corresponds to a given degree of compression of hydrogen in this cylinder. Simultaneously with this process valve S_1 opens and hydrogen from tank H_2 flows into operating cylinder V_1 and then valve S_1 closes.

When cylinder V_2 has been filled with a certain volume of working fluid, valve S_7 is closed and valves S_5 and S_6 are opened. The compressed hydrogen flows through valve S_5 into operating cylinder V_3 of the second compression stage, at the same time working fluid flows through valve S_6 and fluid flow counter D_1 into operating cylinder V_1, where hydrogen compression occurs. During this time, the transfer of compressed hydrogen from the operating cylinder V_2 to the operating cylinder V_3 is completed, so valve S_5 is closed and valves S_2 and S_{12} are opened.

During this period, hydrogen from tank H_2 through open valve S_2 presses working fluid from operating cylinder V_2 into tank T_1 through fluid flow counter D_2 and optical sensor D_6. At the same time, a certain amount of the working fluid will remain on the walls of the operating cylinder due to its viscosity.

The signal to close valves S_2, S_{12} will come after the optical sensor D_6 has detected that the flow of working fluid in the pipeline has been interrupted. During this cycle, fluid flow counter D_2 operates in reverse mode, which allows determining the volume of fluid remaining in the operating cylinder and dispense working fluid in the next cycle. At the end of the cycle, the operating cylinder V_2 is filled with low pressure hydrogen and prepared for a new compression cycle.

Working cycle of hydrogen compression in operating cylinder V_1 occurs in antiphase with respect to the working cycle of cylinder V_2. After closing of valve S_5, valves S_4, S, are opened and compressed hydrogen from cylinder V_1 flows into operating cylinder V_3, but cylinder V_2 is filled with working fluid.

In the next step, simultaneously with the start of hydrogen compression in cylinder V_2, valve S_4 is closed and valves S_1, S_{10} are opened. This allows filling cylinder V_1 with hydrogen and draining the working fluid from the cylinder. Hydrogen from tank H_2 through open valve S_1 squeezes working fluid from operating cylinder V_1 into tank

T_1 through flow counter D_1 and optical sensor D_4. A signal to close valves S_1, S_{10} will come after the optical sensor D_4 determines that there is an interruption of the working fluid flow in the pipeline. The fluid flow counter D_1 works in the same way as fluid flow counter D_2.

After several repetitive cycles, the hydrogen pressure in operating cylinder V_3 reaches its maximum and becomes equal to the pressure in the cylinders V_1, V_2. After this all valves are closed and valves S_3, S_9 are opened, through which working fluid is supplied to operating cylinder V_3 and compressed hydrogen enters buffer cylinder V_4. The degree of compression of hydrogen in cylinder V_3 is regulated by supply of working fluid, the volume of which is determined by the fluid flow counter D_3.

Valves S_3, S_9 are closed after hydrogen has been removed from cylinder V_3, from which the working fluid is removed via fluid flow counter D_3 and optical sensor D_5. This occurs after opening valve S_8 and repeating the cycle of filling cylinder V_3 with compressed hydrogen from cylinders V_1, V_2. The S_8 valve is closed on a signal from optical sensor D_5, and the fluid flow counter D_3 operates in the same way as counters D_1, D_2.

This completes the pressure booster cycle and the accumulation of hydrogen in buffer cylinder V_4. The compressed hydrogen is supplied via valve S_{13} to the dispenser of the refuelling station.

Valve S_{11} serves for bypass of working fluid flow from pump P_1 outlet in cases when valves S_6, S_7, S_9 are closed, while pump P_1 is still switched on. This allows the working fluid removal from cylinders V_1–V_3 to be completed without stopping the P_1 pump.

The peculiarity of the considered compressor design is the use of fluid flow counters to determine the boundary of the compression cycles, so the hydrogen compression ratio is carried out without the use of fluid level sensors installed in the operating cylinders. The signals used to generate switching commands for the valves can be adjusted according to the operating algorithm and current status of the system.

As a result, the reliability of the device is increased, as the control system is continuously informed about the degree of filling of the operating cylinders with working fluid. At the same time, the information provided by the safety loop makes it possible to avoid emergencies in the event that certain sensors are misguided. In this case, the cyclic process can be restored without returning to the initial state of the device and draining the working fluid into the tank T_1 from the working cylinders.

5. DISCUSSION

In order to achieve mass usage of hydrogen in vehicles, an adequate infrastructure and network of hydrogen refuelling stations are needed. The core element of any such filling station is a booster compressor that can ensure the high pressure of hydrogen up to 100 MPa required for refuelling.

The technical features of the hydraulic compressors are optimally adapted to the basic requirements for use as booster compressors in refuelling stations.

The hydraulic compressor concept proposed by the authors can serve as one of the key components in the technological chain that starts with the hydrogen production by the means of electrolysis of water and concludes with the fuel dispensation at a refuelling station.

The technical solution of controlling the operation cycle of the hydraulic compressor using fluid flow counters proposed by the authors provides for continuous control of the hydrogen compression process, which increases the reliability of the control system.

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