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Exergy analysis of a high pressure multistage hydrogen gas storage system

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ABSTRACT

This study presents a parametric study on the performance aspects, through exergy analysis, of the multistage hydrogen gas storage subsystem in a hydropower-based-hydrogen gas fueling station producing 3 kg of hydrogen per hour and storing it. In order to perform an exergy analysis, the following parameters are taken into consideration: (i) mass flow rate of hydrogen (3 kg/h), (ii) inlet pressure of hydrogen (ranging from 1 to 200 bar), (iii) hydrogen storage pressure (ranging from 200 to 900 bar), (iv) dead state temperature (at 25 °C), (v) efficiency of electrical motor (90%), (vi) mechanical efficiency (95%), and (vii) polytropic efficiency (90%). It is obtained that increasing inlet pressure of hydrogen gas decreases the energy consumption for compression and storage process while increasing exergy efficiency. Moreover, it is noticed that increasing storage pressure increases the exergy content of hydrogen gas.

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1. Introduction

Energy is a key element in the interactions between nature and society, and is considered a key input for the environment and sustainable development. Environmental and sustainability issues cover a continuously growing range of pollutants, hazards and ecosystem degradation factors that affect areas ranging from local through regional to global. Some of these concerns arise from observable, chronic effects on, for instance, human health, while others stem from actual or perceived environmental risks such as possible accidental releases of hazardous materials [1].

An increase in the energy consumption of a country provides a positive impact on the economic as well as social development of the country. Moreover, both supply and utilization of cost-effective and clean fuel are particularly significant for

environmental sustainability as well as social, economic and institutional sustainability since energy plays a vital role in industrial and technological developments around the world [2–4]. It is obvious that for transitional period before switching to hydrogen economy the fossil fuel-based-energy systems may still play role in supplying the energy required for various sectors, ranging from residential to industrial and transportation to utility for power and hydrogen production.

The critical global issues in the 21st century will likely include the security of energy reserves for up to 9.19 billion people by 2050 as in a more recent UN forecast [5], the expected global population by the middle of the 21st century, and global warming, mainly caused by CO₂ emissions generated from the combustion of fossil fuels, and environmental pollution created by fossil fuel consumption and production. These factors have led to world population transition, migration, hunger,

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environmental (especially air and water pollution) problems, deteriorating health and disease, terrorism, petroleum and other natural energy resources concerns, and wars. In this regard, the world has reached a level which is not tolerable anymore in the security of energy reserves. As a consequence, investigations of alternative fuels and sustainable energy technologies have recently become important, particularly for future world energy stability. In line with this characteristic, hydrogen and its technologies likely will become one of the most attractive solutions in the near future. Hydrogen is one of the most promising energy carriers for the future, and considered an energy-efficient and low-polluting fuel. When hydrogen is used in a fuel cell to generate electricity or is combusted with air, the only products are water and a small amount of NO_x . Hydrogen is renewable and found in many compounds such as water, fossil fuels, and biomass [6].

Hydrogen produced through non-fossil fuel sources by using the different forms of sustainable energy sources, such as solar, hydropower, wind, nuclear, etc., (so-called: renewable energy based hydrogen production) can be considered to be a prime fuel in meeting some quantity of energy supply and security, transition to hydrogen economy, environmental, social, societal, sectoral, technological, industrial, economical and governmental sustainabilities in a country [7]. Thus, renewable energy based hydrogen system can be one of the best solution for accelerating and ensuring the global energy stability and sustainability. One of the most important parts of the renewable energy based hydrogen system is hydrogen storage unit. Although it has many advantages over most conventional fuels, efficient storage of hydrogen is difficult because of its very low density [8].

For portable and stationary applications, it is known that hydrogen is stored by applying the following methods [9]: (i) high pressure gas cylinders (up to 800 bar), (ii) liquid hydrogen in cryogenic tanks (at 21 K), (iii) adsorbed hydrogen on materials with a large specific surface area (at $T < 100$ K), (iv) Absorbed on interstitial sites in a host metal (at ambient pressure and temperature), (v) Chemically bonded in covalent and ionic compounds (at ambient pressure), (vi) Through oxidation of reactive metals, e.g. Li, Na, Mg, Al, Zn with water. Among these, the most common storage system is high pressure gas cylinders with a maximum pressure of 20 MPa (200 bar). New lightweight composite cylinders have been developed which are able to withstand pressures up to 80 MPa (800 bar) and therefore the hydrogen gas can reach a volumetric density of 36 kg/m^3 , approximately half as much as in its liquid state [9]. In fact, high pressure hydrogen gas storage system is one of the most important parts of the hydrogen gas fueling stations. Generally, the renewable energy assisted hydrogen gas fueling station consists of the following subsystems: (i) Renewable power supply unit, (ii) hydrogen production unit (including gas purification, drying, and cooling units), (iii) hydrogen compression unit with storage component, (iv) dispenser.

In this study, hydrogen gas compression unit with storage component of the hydropower-based-hydrogen gas fueling station [10–12] is considered, and its exergy analysis is conducted for performance assessment. Through a comprehensive literature review, it is evident from the literature works that there are a limited number of studies/reports available on several aspects of hydrogen gas storage systems (e.g. [13–18]). On the other hand, no study has appeared in the literature on

exergy analysis of high pressure multistage hydrogen gas storage systems. Lack of such a work in the literature makes the paper original and becomes the main motivation behind this work. In addition, there are some key reasons (developed from [7,19,20]) to conduct the present study: (i) a new sustainable energy source and/or a new sustainable energy carrier are required because economically available fossil fuel reserves will run out in the future. (ii) It is great interest and significant support to develop hydrogen gas fueling stations as a long term replacement for fossil fuel stations. (iii) Hydrogen is expected to replace some conventional fuels, particularly for the transportation applications (iv) Hydrogen is expected to be a cost-effective fuel for environmentally benign energy systems and applications. (v) Hydrogen appears to be an exergetically efficient fuel in power generation systems. (vi) Environmentally benign and sustainable hydrogen production and utilization will be one of the potential solutions in combating global energy problems [20–22]. (vii) There is an increasing interest in the use of hydrogen for both mobile and stationary applications as environmentally friendly power source. (viii) Sustainable energy sources and energy carriers are required due to the limited availability of fossil fuel reserves and some unavoidable environmental impacts of their utilization. (ix) Requirement of hydrogen gas for portable local and industrial applications as well as transportation applications. (x) Most commonly used and simplest method is to store hydrogen in its natural form as a gas [23,24]. All these obligate the development and installation of hydrogen fueling stations, and the performance analysis and a better comparison of the high pressure hydrogen gas storage systems with single compression effect and multiple compression effect. If one wants to evaluate these thermodynamically, there are two ways: energy analysis through the first law of thermodynamics and exergy analysis through the second law of thermodynamics. Exergy analysis is an essential tool to expose the thermodynamic aspects of a high pressure multistage hydrogen gas storage system [20,25]. In the lights of these explanations, the main objective of the paper is to perform a parametric study on the performance aspects, through exergy analysis, of the high pressure multistage hydrogen gas storage subsystem in a hydropower-based-hydrogen gas fueling station with a production capacity of 3 kg of hydrogen per hour and storing it in gaseous form [11]. In this regard, an original study, this paper aims to introduce some main concepts and parameters about the exergy evaluation of the high pressure multistage hydrogen gas storage subsystem.

2. System description

2.1. Main considerations

The production of hydrogen from non-fossil fuel sources, and the development and application of renewable energy based hydrogen energy technologies becomes crucial in this century for better transition to hydrogen economy. A successful transition to a major role for hydrogen will require much greater cost-effectiveness, fueling infrastructure, consumer acceptance, and a strategy for its basis in renewable energy feedstocks [26]. In addition, various hydrogen fuel-related criteria that are essential in developing an environmentally benign renewable energy

based high pressurized hydrogen gas fueling station in a country are as follows: (i) integration of environmental and energy sustainability issues with development and installation of this station in practice, (ii) improvement of renewable hydrogen fuel supply efficiency, (iii) ensuring the production and storage cost stability in this station, (iv) increasing the environmental and energy sustainability investments of the station, (v) development of appropriate energy and environmental strategies for better efficiency and environmental sustainability of the station, (vi) promoting environmentally benign clean hydrogen production technologies supplying renewable hydrogen to the station, (vii) development of sustainable hydrogen economy infrastructure in terms of renewable hydrogen gas fueling stations, (viii) commercially viable and reliable environmentally benign renewable energy based high pressurized hydrogen gas fueling station, (ix) availability and utilization of renewable energy based technologies for hydrogen production, transportation, distribution, storage and usage, (x) development of university–industry–government partnership programs for encouraging the application of environmentally benign renewable energy based high pressurized hydrogen gas fueling stations, (xi) development of appropriate energy and environmental sustainability laws and programs to encourage the renewable energy based high pressurized hydrogen gas fueling station. Under these considerations, the exergy aspects of high pressure multistage hydrogen gas compression and storage process in hydropower-integrated-hydrogen gas fueling station [11] has been parametrically studied.

2.2. Operating principle of the system

High pressure multistage hydrogen compression and storage system is an important subsystem of a micro hydropower-

integrated-hydrogen production and storage system (micro HIGHPASS) called hydropower-based-hydrogen gas fueling station. A schematic illustration of micro HIGHPASS' operation principle is shown in Fig. 1. As illustrated in Fig. 1, hydrogen gas compression and gas storage subunits have been taken into consideration in the present study.

3. Analysis

In order to perform the exergy analysis of high pressure hydrogen compression and storage systems, including (i) single-stage hydrogen gas compression and storage process, (ii) multistage hydrogen gas compression and storage process, the following steps are considered in the analysis procedure:

- Assumptions,
- Control volumes of high pressure hydrogen gas compression and storage subunits,
- Operating parameters,
- Thermodynamic works (energy and exergy analyses).

3.1. Assumptions

For the exergy analysis of the processes, the following assumptions are made:

- Hydrogen gas is a real gas throughout the compression process. Therefore, compressibility factor for hydrogen is taken into account during the calculations.
- The system and each component run steadily.

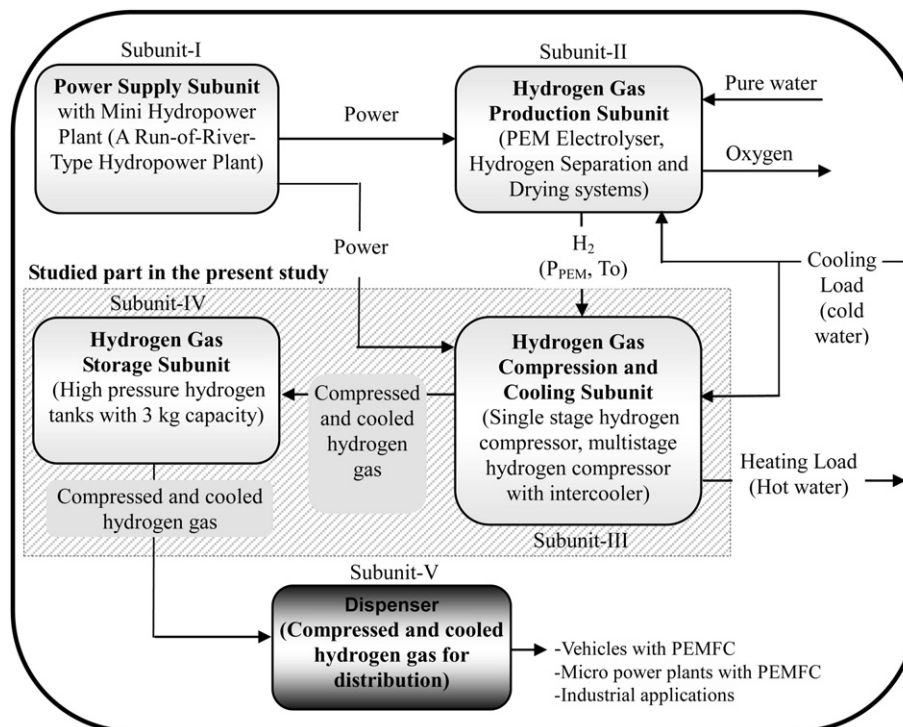


Fig. 1 – A schematic illustration of micro HIGHPASS' operation principle.

- According to thermodynamics, the actual form of compression will usually be between the theoretical conditions of isothermal compression and isentropic compression, which represent a low limit and an upper limit of the work of compression respectively [27].
- The compression of hydrogen is a reversible polytropic path, where PV^n is constant. Here, n is the polytropic exponent that depends on the nature of the gas and the details of the compression process. When polytropic exponent, n , is greater than k , heat is supplied to the gas during the compression. On the other hand, when $n < k$, heat is rejected by the gas during compression. According to this assumption, hydrogen gas compression stage has been selected to be control volume [28].
- The polytropic efficiency, mechanical efficiency and motor efficiency are taken as 0.90, 0.95 and 0.9.
- A piston compressor is employed for hydrogen gas compression.
- The compression ratio for each stage of the compressor is taken to be 6 [28].
- Intercooling processes in the compression stages of the compressor are completely performed because water is used as coolant.
- The heat exchangers are assumed to be adiabatic.
- Inlet and outlet temperature of cooling water are taken as 20 °C and 90 °C.
- The required electricity for the compression processes is supplied from a run-of-river type hydropower plant.
- Compression and storage capacities are taken as 3 kg/h and 3 kg of hydrogen gas, respectively.
- There are no pressure and temperature drops in the connection pipes.
- There are no hydrogen gas leakages throughout the system.
- Kinetic and potential energy changes are neglected during the process.
- Thermodynamic properties are taken from the Nist source [29] because of high temperatures and pressures. The results obtained in this study can change based on the thermodynamic properties that will be taken from other sources. In this study, the Nist [29] is the source of the thermodynamic properties.

3.2. Control volumes

In this study, two different systems which are single-stage hydrogen gas compression and storage system and multistage hydrogen gas compression and storage system, are considered for the analysis. Figs. 2 and 3 illustrate the control volumes of these systems respectively. Considering Figs. 2 and 3, the operating principles of the systems are presented as below. As shown in Fig. 2, the single-stage hydrogen compression and storage is the first model considered for high pressurized hydrogen gas. The hydrogen gas that has the operating pressure and temperature of the PEM electrolyser is cooled to 25 °C of environmental temperature at constant pressure by using a gas-to-liquid shell-and-tube heat exchanger at constant pressure that is probably the most common type of heat exchangers in industrial applications. As the second step, this hydrogen gas enters the compression

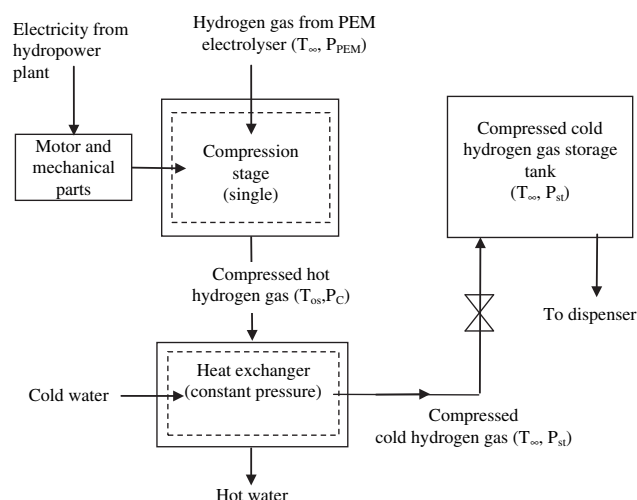


Fig. 2 – Control volume model of the single stage hydrogen gas compression and storage system ($P_c \equiv P_{st}$).

stage of the compressor, and is pressurized in accordance with the compression ratio of the compressor. During the compression, hydrogen gas in the compression stage takes heat.

The hydrogen gas that increases the pressure and temperature at the end of the compression stage is cooled to 25 °C at constant pressure. This process has been represented by a gas-to-liquid shell-and-tube heat exchanger as in Fig. 2. In this process, the high pressurized hydrogen gas loses heat to the cooling water in the heat exchanger at constant pressure. The water used for cooling process of hydrogen gas is stored to use at heating pure water required for hydrogen production in PEM electrolyser of the hydropower-integrated-hydrogen gas fueling station. At the end of these processes, the high pressurized and low temperature hydrogen gas is directly transferred to the storage tank which is non-load-bearing non-metal liner axial and hoop wrapped with resin-impregnated continuous filament [28,30].

As a general difference from the operating principle of the single-stage hydrogen gas compression system, hydrogen gas is cooled to 25 °C at the end of each compression stage of the multistage hydrogen gas compression and storage system as shown in Fig. 3.

3.3. Operating parameters

The following operating parameters are considered for analysis: (i) mass flow rate of hydrogen gas (assumed to be 3 kg of hydrogen per hour), (ii) hydrogen storage capacity (assumed to be 3 kg), (iii) reference environment pressure as 1 bar, (iv) reference environment temperature as 298.15 K, (v) inlet temperature of hydrogen gas entering the compressor as 298.15 K, (vi) inlet pressure range of hydrogen gas entering the compressor from 1 to 200 bar, (vii) outlet pressure range of hydrogen gas leaving the compressor as from 200 to 900 bar, (viii) storage pressure range of hydrogen from 200 to 900 bar, (ix) polytropic efficiency as 90%, (x) mechanical efficiency as 95% and (xi) motor efficiency as 90%.

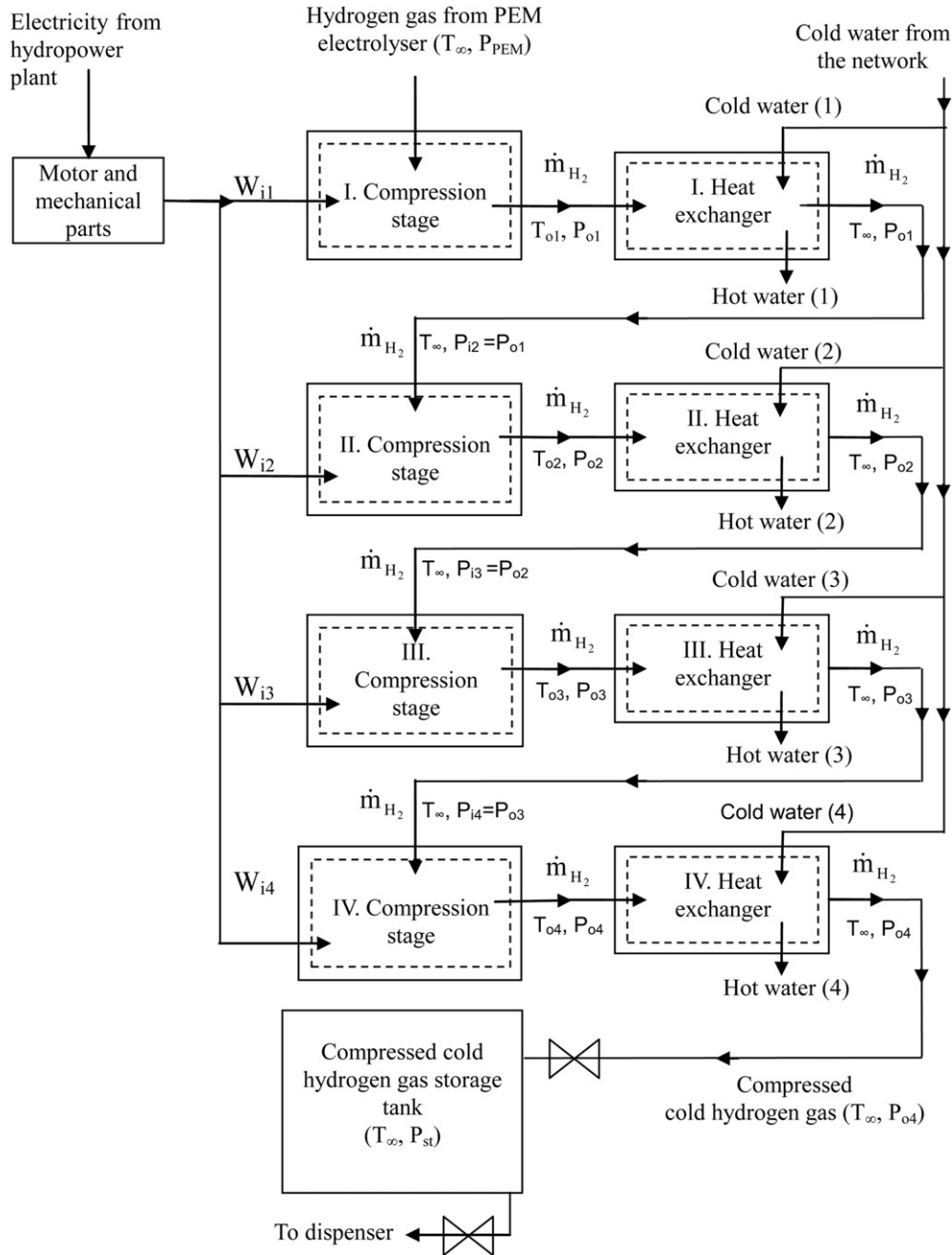


Fig. 3 – Control volume model of the multistage hydrogen gas compression and storage system ($P_{o4} \equiv P_{st}$; P_{st} is the pressure of the storage tank).

3.4. Thermodynamic studies

In the scope of the thermodynamic analyses, the energy analysis of the system has been achieved in terms of the first law of thermodynamic while its exergy analysis is performed in terms of the second law of thermodynamics.

3.4.1. Energy analysis

3.4.1.1. Calculations of specific heat ratio (k) and polytropic exponent (n). In this section, first, the specific heat ratio (k) has been calculated by using Eq. (1) accounting the specific heat at

constant pressure (c_p) and the specific heat at constant volume (c_v) for the given reference environment temperature and the Inlet pressure range of hydrogen gas entering the compressor. For this purpose, the specific heat values have been taken from [29] at the given temperature and pressure. Table 1 presents the specific heat ratios for the given inlet pressures of hydrogen gas entering the compressor as

$$k = \frac{c_p}{c_v} \quad (1)$$

The polytropic exponent is calculated by using Eq. (2) accounting the specific heat ratio and polytropic efficiency

($\eta_p = 0.90$) [31]. The values of polytropic exponent for reference environment temperature and the inlet pressures of hydrogen gas entering the compressor are given in Table 1.

$$\frac{n}{n-1} = \frac{k}{k-1} \eta_p \quad (2)$$

3.4.1.2. *Pressure ratio of each compression stage in the compressor (r_p)*. Pressure ratio of each compression stage in the compressor (r_p) is calculated by

$$r_p = \left(\frac{P_o}{P_i} \right)^{1/y} \quad (3)$$

where P_o is pressure of hydrogen gas leaving the compressor and entering the storage tank; P_i , pressure of hydrogen gas entering the compressor; y , stage number.

3.4.1.3. *Outlet temperature of hydrogen gas leaving the compression stage (T_o)*. The outlet temperature of hydrogen gas leaving the compression stage is calculated by [32]:

$$T_o = (r_p)^{(n-1)/n} T_\infty \quad (4)$$

where T_o is outlet temperature of hydrogen gas leaving the compression stage; T_∞ , inlet temperature of hydrogen gas entering the compression stage at the reference environment temperature; n , polytropic exponent.

3.4.1.4. *Compressibility factor*. Compressibility factor has been taken into account because hydrogen gas is considered to be real gas not ideal gas. In order to estimate the required energy for the compression of hydrogen gas, the mean compressibility factor (Z_m) needs to be calculated [33]. The density of hydrogen gas entering and leaving the compression stages:

$$\rho = \frac{100P}{ZR_u T} \quad (5)$$

where P is inlet and outlet pressure of hydrogen gas entering and leaving the compression stage; T , inlet and outlet temperature of hydrogen gas entering and leaving the compression stage; R_u , universal gas constant; Z , compressibility factor for hydrogen gas at the inlet and outlet conditions.

After substituting Eq. (5) into Eq. (6) and making some algebraic manipulations, the compressibility factor becomes

$$Z = 1 + \left(B_0 - \frac{A_0}{R_u T} - \frac{C_0}{R_u T} \right) \rho + \left(b - \frac{a}{R_u T} \right) \rho^2 + \frac{a\alpha}{R_u T} \rho^5 + \frac{c\rho^2}{R_u T} [(1 + \gamma\rho^2) \exp(-\gamma\rho^2)] \quad (6)$$

where A_0 ($=9.860848$ (m^3/kmol)² kPa), B_0 ($=0.018041$ (m^3/kmol)), C_0 ($=39429.61$ (m^3/kmol)² KkPa), a ($=-0.93433$ (m^3/kmol)³ kPa),

b ($=0.00018$ (m^3/kmol)²), c ($=-24939.1$ (m^3/kmol)³ K² kPa), α ($=-3.4 \times 10^{-6}$ (m^3/kmol)³), γ ($=0.00189$ (m^3/kmol)²) are constants for hydrogen gas [34].

After the compressibility factors for inlet (Z_i) and outlet (Z_o) of hydrogen gas have been estimated, the mean compressibility factor is calculated as

$$Z_m = \frac{Z_i + Z_o}{2} \quad (7)$$

3.4.1.5. *Polytropic and actual works of the compression stages*. Based on the polytropic exponent (n), mean compressibility factor (Z_m), mass flow rate of hydrogen gas (\dot{m}_{H_2}), compression ratio (r_p), gas constant of hydrogen gas (R_{H_2}) and inlet temperature of hydrogen gas entering the compression stage (T_∞), total polytropic work of compression stages (\dot{W}_p) is calculated below, after including the mean compressibility factor in the polytropic work of the stage [35]:

$$\sum_{j=1}^y \dot{W}_{p,j} = \sum_{j=1}^y \left(\dot{m}_{H_2} Z_m \frac{n}{n-1} R_{H_2} T_\infty \left[(r_p)^{(n-1)/n} - 1 \right] \right)_j \quad (8)$$

where y stands for the compression stage number. $y = 1, 2, 3$, and 4 for the multistage hydrogen gas compression in this study. But, for the single-stage hydrogen gas compression unit, $y = 1$.

The actual work of the compression stage (\dot{W}_{ac}) is calculated below, depending on the polytropic work of compression stage (\dot{W}_p) and polytropic efficiency (η_p) that is assumed to be 0.90:

$$\dot{W}_{ac} = \sum_{j=1}^y \dot{W}_{p,j} / \eta_p \quad (9)$$

3.4.1.6. *Total actual work taken from the hydropower plant*. The actual work transmitted to compressor axis (\dot{W}_{aca}) is calculated below, after accounting the actual work of compression stage and the mechanical efficiency (η_{mech}) of 0.95:

$$\dot{W}_{aca} = \frac{\dot{W}_{ac}}{\eta_{mech}} \quad (10)$$

The actual work transmitted to electricity motor axis (\dot{W}_{aem}) is calculated below, after accounting the actual work transmitted to compressor axis and the electricity motor efficiency (η_{em}) of 0.90:

$$\dot{W}_{aem} = \frac{\dot{W}_{aca}}{\eta_{em}} \quad (11)$$

Considering Eqs. (9)–(11), the total actual work taken from the run-of-river-type-hydropower plant that is called the

Table 1 – Specific heat ratio and polytropic exponent for the given Inlet pressures of hydrogen gas entering the compressor and reference environment temperatures.

| P_i | 1 bar | 10 bar | 20 bar | 30 bar | 40 bar | 50 bar | 100 bar | 150 bar | 200 bar |
|-------|-------|--------|--------|--------|--------|--------|---------|---------|---------|
| k | 1.405 | 1.406 | 1.408 | 1.409 | 1.411 | 1.412 | 1.417 | 1.420 | 1.422 |
| n | 1.435 | 1.437 | 1.439 | 1.440 | 1.442 | 1.443 | 1.449 | 1.452 | 1.455 |

actual work of hydrogen gas compression and storage subunit is calculated by

$$\dot{W}_{\text{tacs}} = \frac{\sum_{j=1}^y (\dot{m}_{\text{H}_2} \times Z_m \times \frac{n}{n-1} \times R_{\text{H}_2} \times T_{\infty} \times [(r_p)^{(n-1)/n} - 1])_j}{\eta_p \times \eta_{\text{mech}} \times \eta_{\text{em}}} \quad (12)$$

3.4.1.7. *Cooling load for hydrogen gas before storage.* The required cooling load (\dot{Q}_{cl}) for reducing the temperature of hydrogen gas to reference environment temperature is calculated by

$$\begin{aligned} \sum_{j=1}^y \dot{Q}_{\text{cl},j} &= (\dot{m}_{\text{H}_2} \times c_{p,\text{H}_2} \times (T_{i,\text{H}_2} - T_{o,\text{H}_2}))_j \\ &= ((\dot{m}_w \times c_{p,w} \times (T_{ow} - T_{iw})))_j \end{aligned} \quad (13)$$

where \dot{m}_{H_2} describes the mass flow rate of hydrogen gas; c_{p,H_2} , specific heat of high pressurized hydrogen gas; T_{o,H_2} , outlet temperature of high pressurized hydrogen gas leaving the heat exchanger; T_{i,H_2} , inlet temperature of high pressurized hydrogen gas entering the heat exchanger; \dot{m}_w , the mass flow rate of cooling water; $c_{p,w}$, specific heat of cooling water; T_{ow} , outlet temperature of cooling water leaving the heat exchanger; T_{iw} , inlet temperature of cooling water entering the heat exchanger.

3.4.1.8. *Energy efficiency of high pressurized hydrogen gas compression and storage system.* In order to determine the energy efficiency of the high pressurized hydrogen gas compression and storage system, the parameters affecting the process, considering Figs. 2 and 3, are illustrated as in Fig. 4. According to the first law of thermodynamics, the energy efficiency of high pressurized hydrogen gas compression and storage system can be written as

$$\eta_{\text{ene}}^{\text{sys}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\dot{m}_{\text{H}_2} \times h_{o,\text{H}_2}(T_{\infty}, P_{\text{st}})}{\dot{W}_{\text{tacs}} + \sum_{j=1}^y \dot{Q}_{\text{cl},j} + \dot{m}_{\text{H}_2} \times h_{i,\text{H}_2}(T_{\infty}, P_{\text{PEM}})} \quad (14)$$

Here, it should be emphasized that the value of energetic efficiency of the high pressurized hydrogen gas compression and storage system can vary by depending on the definition of energetic efficiency of the system.

3.4.2. Exergy analysis

In order to find out the actual behavior of the system, the exergy analysis should be performed, which indicates the losses and their locations in the system. In order to perform the exergy analysis of the single and multistage high pressurized hydrogen gas compression and storage system, the following general procedure, considering Figs. 2–4, is taken into consideration.

3.4.2.1. *Total exergy input.* In general, depending on the process and/or system, the general exergy balance is written for a steady-state steady-flow process as follows:

$$\sum \dot{Ex}_{\text{in}} = \sum \dot{Ex}_{\text{out}} + I \quad (15)$$

In the high pressurized hydrogen gas compression and storage system, the exergy interaction includes exergy

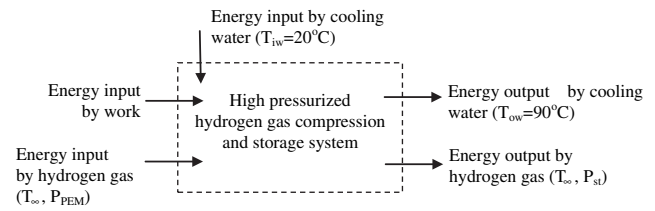


Fig. 4 – General energy interaction of high pressurized hydrogen gas compression and storage system.

transfer by work, exergy transfer by mass and exergy transfer by heat. Considering Figs. 2, 3 and 5, the exergy inputs and exergy output can be written as

$$\sum_{j=1}^y \dot{Ex}_{i,j} = \dot{Ex}_i^m + \dot{Ex}_i^w + \sum_{j=1}^y \dot{Ex}_{i,j}^Q \quad (16)$$

where

$$\sum_{j=1}^y \dot{Ex}_{i,j}^Q = \dot{Q}_{\text{cl},j} \times \left(1 - \frac{T_{\infty}}{T_{i,\text{H}_2}}\right)_j \quad (17)$$

$$\dot{Ex}_i^w = \dot{W}_{\text{tacs}} \quad (18)$$

$$\begin{aligned} \dot{Ex}_i^m &= \dot{m}_{\text{H}_2} \times [(\dot{Ex})_{\text{H}_2}^{\text{ch}} + (\dot{Ex})_{\text{H}_2}^{\text{ph}}] = \dot{m}_{\text{H}_2} \times (\dot{Ex})_{\text{H}_2}^{\text{ph}} \\ &= \dot{m}_{\text{H}_2} \times (h_{@P_{\text{is}}, T_{\text{is}}} - h_{\infty} - T_{\infty} \times (s_{@P_{\text{is}}, T_{\text{is}}} - s_{\infty})) \end{aligned} \quad (19)$$

where P_{is} describes inlet pressure of the compression stage; T_{is} inlet temperature of the compression stage; T_{o,H_2} . Here, physical exergy of hydrogen gas (thermomechanical exergy) is only taken into account since no chemical reaction takes place within the system.

3.4.2.2. Total exergy output.

$$\sum \dot{Ex}_o = \dot{Ex}_o^m \quad (20)$$

$$\dot{Ex}_o^m = \dot{m}_{\text{H}_2} \times [(\dot{Ex})_{\text{H}_2}^{\text{ch}} + (\dot{Ex})_{\text{H}_2}^{\text{ph}}]_j = \dot{m}_{\text{H}_2} \times (\dot{Ex})_{\text{H}_2}^{\text{ph}} = \dot{m}_{\text{H}_2} \times (h_{@P_{\text{os}}, T_{\text{os}}} - h_{\infty} - T_{\infty} \times (s_{@P_{\text{os}}, T_{\text{os}}} - s_{\infty}))$$

where P_{os} describes inlet pressure of the compression stage; T_{os} , inlet temperature of the compression stage; T_{o,H_2} .

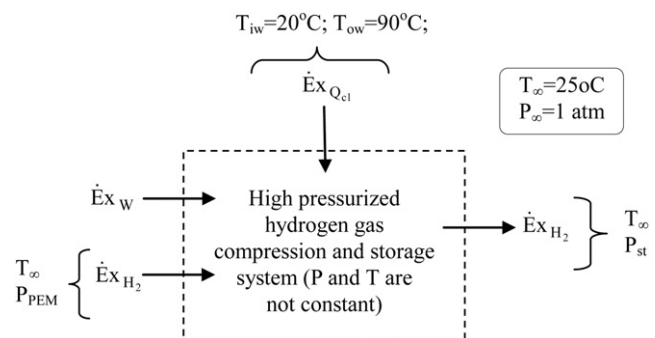


Fig. 5 – General exergy interaction of high pressurized hydrogen gas compression and storage system.

3.4.2.3. *Exergy efficiency of high pressurized hydrogen gas compression and storage system.* The following types of exergy efficiency can be defined for steady-flow processes:

The exergy efficiency can be written as

$$\eta_{ex} = \frac{\dot{E}x_o}{\dot{E}x_i} \quad (21)$$

The rational exergy efficiency: This may be preferred for the processes where no work or heat transfer is involved [36,37] as

$$\eta_{ex} = \frac{\dot{E}x_{desired\ output}}{\dot{E}x_{used}} \quad (22)$$

where the desired exergy output is determined by examining the function of the system, but will also include exergy related to any useful by-product produced by the system. Additionally, Zvolinschi et al. [38] use the following equation to calculate the exergy efficiency:

$$\eta_{ex} = \frac{\dot{E}x_{out}^{useful}}{\dot{E}x_{in}^{total}} \quad (23)$$

The useful exergy output includes both the exergy of the desired product as well as exergy of useful by-products. This is similar to the efficiency used by Kotas [36], but with slightly different notation [37].

In this study, the exergy efficiency of whole system is defined as

$$\eta_{ex}^{sys} = \frac{\dot{E}x_{H_2}^{st}}{\dot{E}x_i^w + \sum_{j=1}^y \dot{E}x_{ij}^Q + \dot{E}x_i^m} \quad (24)$$

where $\dot{E}x_{H_2}^{st}$ describes the exergy by high pressurized hydrogen gas entering the storage tank; $\sum_{j=1}^y \dot{E}x_{ij}^Q$, exergy by total cooling load; $\dot{E}x_i^m$, the exergy by hydrogen gas entering the compression stage. Here, it should be emphasized that the value of exergy efficiency of the high pressurized hydrogen gas compression and storage system can vary by depending on the definition of exergy efficiency of the system.

3.4.2.4. *Exergy efficiency of each compression stage in Fig. 3.* The exergy efficiency for each compression stage is defined as

$$\eta_{ex}^{sta} = \frac{\dot{E}x_{H_2,o}^{sta} - \dot{E}x_{H_2,i}^{sta}}{\dot{W}_p / \eta_p} \quad (25)$$

where $\dot{E}x_{H_2,i}^{sta}$ describes the flow exergy of high pressurized hydrogen gas entering the compression stage; $\dot{E}x_{H_2,o}^{sta}$, the flow exergy of high pressurized hydrogen gas leaving the compression stage.

3.4.2.5. *Exergy efficiency of each heat exchanger in Fig. 3.* The exergy efficiency for each heat exchanger is calculated as

$$\eta_{ex}^{he} = \frac{\dot{E}x_{co}^w - \dot{E}x_{ci}^w}{\dot{E}x_{hi}^{H_2} - \dot{E}x_{ho}^{H_2}} \quad (26)$$

where $\dot{E}x_{co}^w$ indicates the exergy output by hot water; $\dot{E}x_{ci}^w$, the exergy input by cold water; $\dot{E}x_{hi}^{H_2}$ the exergy input by hot hydrogen gas; $\dot{E}x_{ho}^{H_2}$ the exergy output by cooled hydrogen gas.

3.4.2.6. *Estimation of stored exergy in the tank.* The exergy rate of stored gaseous hydrogen includes the chemical and

physical exergies of hydrogen gas, and can be estimated as below by depending on the temperature and pressure within the storage tank.

$$\begin{aligned} \dot{E}x_{H_2}^{st} &= \dot{m}_{H_2} \times \left[(\dot{E}x)_{H_2}^{ch} + (\dot{E}x)_{H_2}^{ph} \right] \\ &= \dot{m}_{H_2} \times \left[\left(ex_{H_2}^{ch} \right) + \left(h_{@P_{st}, T_{\infty}} - h_{\infty} - T_{\infty} \times (s_{@P_{st}, T_{\infty}} - s_{\infty}) \right) \right] \end{aligned} \quad (27)$$

Here, the chemical exergy of hydrogen gas is taken to be 118.299 MJ/kg or 32.86 kWh/kg [36].

4. Results and discussion

In this study, a parametric study is conducted on the performance aspects, through exergy analysis, of the high pressurized multistage hydrogen gas storage subsystem in a hydropower-based-hydrogen gas fueling station producing 3 kg of hydrogen per hour and storing it in gaseous form. Here, a single-stage high pressurized hydrogen gas compression and storage system and a four-stage high pressurized hydrogen gas compression and storage system are taken into consideration. In this regard, the variations of the parameters are discussed by depending on the inlet pressure of hydrogen gas entering the compression stage and the pressure of the storage unit as given in Figs. 6–8.

Fig. 6a presents the variations of the exergy efficiency of the single-stage high pressurized hydrogen gas compression and storage system as a function of the inlet pressure of hydrogen gas entering the compression stage while Fig. 6b illustrates the variations of its exergy efficiency as a function of hydrogen gas storage pressure. In these figure, the comparisons are performed for 3 kg hydrogen gas per hour. As shown in Fig. 6a, the system exergy efficiency increases with the rise of inlet pressure of hydrogen gas entering the compression stage while it decreases with increasing pressure of hydrogen gas entering the storage tank (or hydrogen storage pressure) as shown in Fig. 6b. For instance, according to Fig. 6a and b, in case of 10 bar of inlet pressure of hydrogen gas, the exergy efficiency is calculated to be 35.88% at 400 bar of constant hydrogen gas storage pressure. When the hydrogen gas storage pressure increases from 200 to 800 bar the exergy efficiency of the system decreases from 43.30% to 30.25% at 10 bar of constant inlet pressure of hydrogen gas. In case of 40 bar of inlet pressure of hydrogen gas, the exergy efficiency is calculated to be 35.89% at 400 bar of constant hydrogen gas storage pressure. For 40 bar of constant inlet pressure of hydrogen gas, it is found that the exergy efficiency is ranging from 71.68% to 49.93% for hydrogen gas storage pressure from 200 to 800 bar.

Fig. 7a presents the variations of the exergy efficiency of four-stage high pressurized hydrogen gas compression and storage system as a function of the inlet pressure of hydrogen gas entering the compression stage while Fig. 7b illustrates the variations of its exergy efficiency as a function of hydrogen gas storage pressure. As shown in Fig. 7a, the exergy efficiency of four-stage high pressurized hydrogen gas compression and storage system goes up with the increase of inlet pressure of hydrogen gas entering the compression stage while it decreases with increasing pressure of hydrogen gas entering the storage tank (or hydrogen storage pressure) as shown in Fig. 7b. For instance, according to Fig. 7a and b, in case of 10 bar of inlet pressure of hydrogen gas, the exergy efficiency is

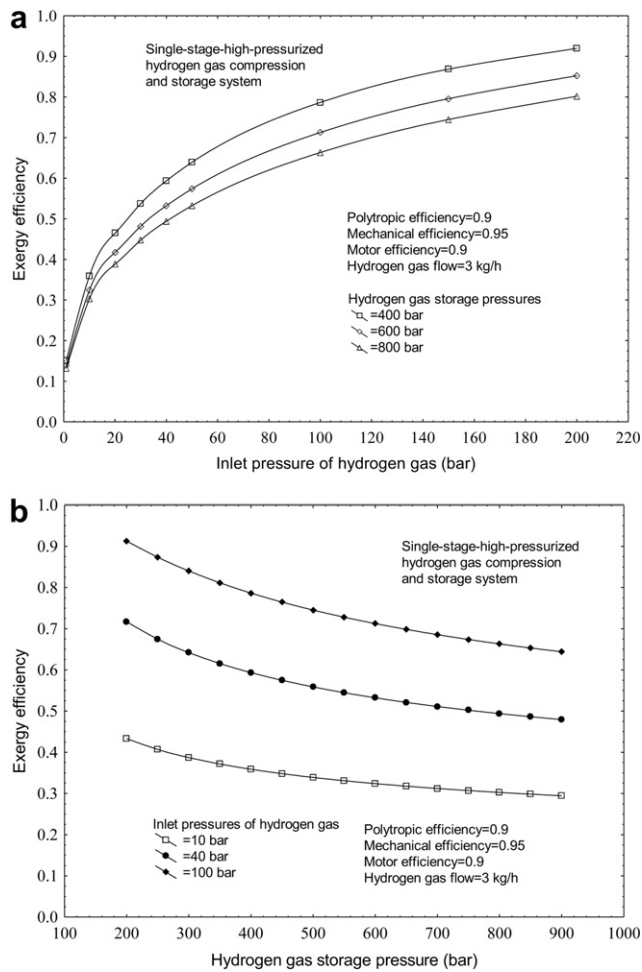


Fig. 6 – (a) Variations of the exergy efficiency of the single-stage high pressurized hydrogen gas compression and storage system as a function of the inlet pressure of hydrogen gas entering the compression stage. (b) Variations of the exergy efficiency of the single-stage high pressurized hydrogen gas compression and storage system as a function of hydrogen gas storage pressure.

calculated to be 66.07% at 400 bar of constant hydrogen gas storage pressure. When the hydrogen gas storage pressure increases from 200 to 800 bar the exergy efficiency of the system decreases from 70.63% to 62.27% at 10 bar of constant inlet pressure of hydrogen gas. In case of 40 bar of inlet pressure of hydrogen gas, the exergy efficiency has been calculated to be 80.17% at 400 bar of constant hydrogen gas storage pressure. For 40 bar of constant inlet pressure of hydrogen gas, it is found that the exergy efficiency is ranging from 85.87% to 75.07% for hydrogen gas storage pressure from 200 to 800 bars. As understood from the above important results, the higher inlet pressure of hydrogen gas entering hydrogen gas compression and storage system is, the higher exergy efficiency of the system is. In this regard, it should be emphasized that the system exergy efficiency as shown in Figs. 1 and 2 is mainly based on the inlet pressure of hydrogen gas entering the system at a constant storage pressure of hydrogen gas in the storage tank. In this situation, the system exergy efficiency

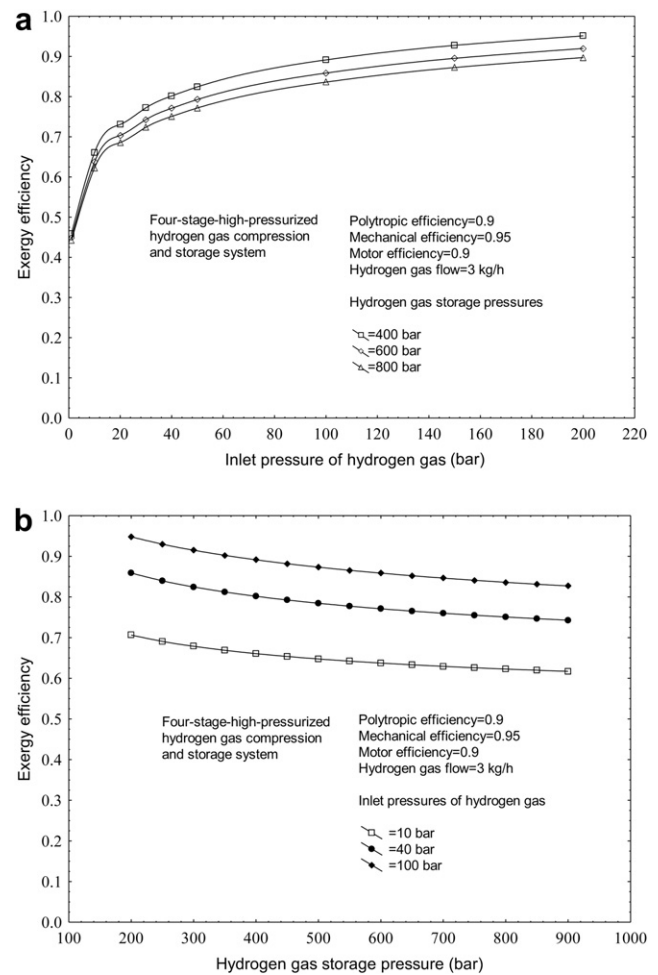


Fig. 7 – (a) Variations of the exergy efficiency of four-stage high pressurized hydrogen gas compression and storage system as a function of inlet pressure of hydrogen gas entering compression stage. (b) Variations of the exergy efficiency of four-stage high pressurized hydrogen gas compression and storage system as a function of hydrogen gas storage pressure.

increases with the increase of inlet pressure of hydrogen gas entering the system. On the other hand, at a constant inlet pressure of hydrogen gas, the exergy efficiency becomes less with the increase of the storage pressure of hydrogen gas. Thus, it is suggested that, in order to save more and more energy and to obtain higher exergy efficiency, the inlet pressure of hydrogen gas entering the system should be selected as high as possible during the single-stage hydrogen gas compression process.

Fig. 8 presents the comparison of exergy efficiencies of the single-stage and four-stage high pressurized hydrogen gas compression and storage system as a function of hydrogen gas storage pressure at constant inlet pressure of hydrogen gas. For this comparison, the polytropic efficiencies of the stages in the compressor are taken to be 0.9, the inlet pressure of hydrogen gas entering the first stage of the compressor is considered to be 20 bars as constant. As shown in Fig. 8, the exergy efficiencies of the single-stage and four-stage high pressurized

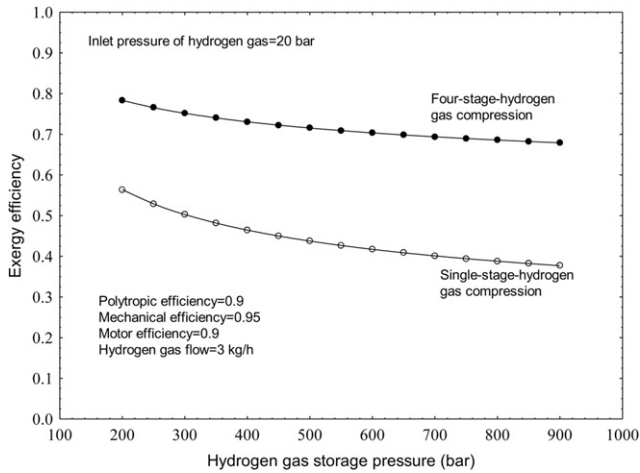


Fig. 8 – Comparison of exergy efficiencies of the single-stage and four-stage high pressurized hydrogen gas compression and storage system as a function of hydrogen gas storage pressure.

hydrogen gas compression and storage systems decrease with the rise of hydrogen gas storage pressure from 200 to 900 bar. So, increasing the stage number increases the system exergy efficiency. For a constant inlet pressure (20 bar) of hydrogen gas, it is estimated that the exergy efficiency of the single-stage high pressurized hydrogen gas compression and storage system ranges from 56.39% to 37.70% while the exergy efficiency of four-stage high pressurized hydrogen gas compression and storage system ranges from 78.32% to 67.90% with increasing hydrogen gas storage pressure from 200 to 900 bar. Thus, in case of the constant inlet pressure of hydrogen gas, the more compression stage number is the higher exergy efficiency of the system increases. However, increasing hydrogen gas storage pressure indicates that both systems have lower exergy efficiency. Accordingly, it is recommended that, in terms of energy saving and exergy efficiency, the stage number of the compressor should be selected as high as possible by taking into consideration the appropriate stage numbers preferred in the practical applications because multistage hydrogen gas compression process is more energetic and exergy than the single-stage hydrogen gas compression process.

5. Conclusions

This paper has presented a parametric investigation on the exergy aspects of the single-stage and four-stage high pressurized hydrogen gas compression and storage subsystem in a hydropower-based-hydrogen gas fueling station producing 3 kg of hydrogen per hour and storing it. In this regard, the following concluding remarks can be drawn from this study:

- For the constant inlet and storage pressures of hydrogen gas, the single-stage hydrogen gas compression and storage system requires more power than the four-stage single-stage hydrogen gas compression and storage system. This

reduces the exergy efficiency of the system and increases the cost of hydrogen gas compression process.

- For a constant hydrogen gas storage pressure, increasing inlet pressure of hydrogen gas increases the exergy efficiency of the system and decreases the power demand for compression. However, an increase of the hydrogen gas storage pressure decreases the exergy efficiency of the system.

Accordingly, it is recommended that, for better exergy efficiency and better energetic sustainability in hydrogen gas compression processes, the multistage hydrogen gas compression processes should be selected, and the compression stage number should be preferred as high as possible fitting to the practical applications.

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