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Metal alloys for the new generation of compressors at hydrogen stations: Parametric study of corrosion behavior

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ABSTRACT

Compressors are one of the most costly components at hydrogen stations, which leads to the high price of hydrogen production. The substitution of a solid piston with ionic liquid is a promising option that may solve some of the challenges related to conventional reciprocating compressors and, consequently, significantly reduce the final cost of hydrogen production. The correct choice of ionic liquid and construction materials is critical for avoiding significant corrosion problems. Hence, the objective of this study is to evaluate the compatibility of various austenitic stainless steels and nickel-based alloys as construction materials in contact with 80 °C ionic liquids in an ionic liquid hydrogen compressor, considering the role of parameters such as the temperature, viscosity, ionic liquid cation and anion, and water absorption.

The results show that temperature contributes to increasing the corrosion rate. However, even at 80 °C, the very low corrosion current densities proved that all of the tested alloys are safe to use as construction materials. AISI 347 showed very high corrosion resistance in all of the ionic liquids. The highest corrosion resistance among all of the tested alloys was observed in trihexyltetradecylphosphonium bis (trifluoromethylsulfonyl) imide, which had a relatively high viscosity and the lowest water content.

1. Introduction

Many environmental analyses show a strong connection between CO_2 emissions, due to fossil fuel consumption, and global warming [1]. Therefore, over the last several decades, attention has been given worldwide towards sustainable solutions that can reduce CO_2 emissions. Currently, more than 95% of all global energy in the transport sector is supplied by fossil fuels. This sector is responsible for over 23% of all energy-related CO_2 emissions [2,3]. In this context, fuel cell vehicles have gained attention as a long-term solution that would enable the use of renewable energy for transportation with zero carbon and particle emission [4]. It is expected that with a 25% share of fuel cell electric vehicles on the roads by 2050, the cumulative transport-related carbon emissions will be reduced by up to 10% [5].

To establish a solid ground for the significant market penetration of fuel cell vehicles, challenges such as fast refueling, long driving range and high energy efficiency must be overcome. To produce fuel cell vehicles with a driving range that is comparable with the current technologies based on fossil fuels, on-board high-pressure hydrogen storage seems to be a promising option. The high-pressure storage of hydrogen in tanks requires the compression of hydrogen to more than 700 bar at refueling stations and the cooling of hydrogen to approximately −40 °C before refueling [6]. On average, compression processes consume 11.3% of the energy contained in hydrogen fuel [7] and are thus viewed as the most costly part of hydrogen infrastructure. Compression and storage compromise approximately 75% of the hydrogen compression, storage, and dispensing (CSD) costs for the pipeline delivery of hydrogen and forecourt hydrogen production [8]. Improving the efficiency and reducing the power consumption of compressors at hydrogen refueling stations can play significant roles in decreasing the final costs of hydrogen production [8].

Liquid piston compressor is a reliable approach in this regard.

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Substituting the solid piston with liquid can address many of the restrictions faced by most conventional reciprocating compressors, such as reducing several of the moving parts, simpler sealing system, the possibility of having a non-cylindrical working chamber and geometry optimization to extract heat from the gas by the liquid during the compression procedure [9]. All of these advantages may decrease the production cost and result in more efficient compressors with longer life spans [10]. A significant improvement in efficiency and a 50% reduction in cost compared with a traditional hydrogen compressor with the same flow rate and compression ratio has been reported for a single prototype unit that uses hydraulic oil to compress hydrogen [11]. However, selecting the appropriate liquid is a fundamental choice in this regard. Some liquids may decompose at elevated temperature, as reported previously for hydraulic oils [11].

Ionic liquids with outstanding properties, such as being liquid at room temperature, negligible vapor pressure together with good lubrication properties, high temperature stability, high chemical stability, low compressibility and low solubility of gasses, have attracted the attention of many engineers for use as a promising performance fluid in hydraulic and pneumatic applications [12]. Substituting lubrication oil with ionic liquid in pumps and compressors [12,13], substituting water with ionic liquid for lubrication operating in liquid ring compressor [14] and vacuum pumps [15], and finally substituting hydraulic oil with an appropriate ionic liquid in a diaphragm pump [15] are some examples of ionic liquids operating in hydraulic and pneumatic applications. These options will lead to fewer mechanical losses and, ultimately, efficiency improvements [12,15].

In all of the above mentioned applications, corrosion is an important factor that should be considered when selecting a suitable combination of ionic liquids and construction materials to avoid serious problems such as reduced efficiency, leakage of explosive gases, reduced strength, contamination of the produced products, and costly maintenance. Incorrect choices of either the ionic liquid or construction material may result in severe corrosion problems, even at ambient temperature. Serious corrosion problems in copper, aluminum and carbon steel have been observed in corrosion studies of these metals and alloys in several imidazolium- and pyrrolidinium-based ionic liquids at 25 °C [16]. In another study, the corrosion behaviors of stainless steel 316 and carbon steel 1018 were investigated in four different imidazolium-based ionic liquids for solar collectors at ambient temperature. The results showed active/passive behavior and outstanding corrosion resistance in ionic liquids, except in those that contained a chloride anion [17]. Additionally, the pitting corrosion of AISI and severe corrosion of copper in an aluminum chloride/1-ethyl-3-methylimidazolium chloride ionic liquid have been reported at ambient temperature [18]. A similar study showed an outstanding corrosion resistance of 304 SS and severe corrosion behavior of titanium in this ionic liquid [19].

In hydraulic and pneumatic industries, an increase in the operating fluid temperature due to several reasons, such as high frequencies, friction and heat absorption from other media in the system, may happen. Consequently, additional attention must be paid to the corrosion behavior of engineering alloys in ionic liquids at elevated temperatures.

The corrosion behavior of copper, nickel, AISI 1018 steel, brass, Inconel 600 in 1-butyl-3methyl-imidazolium bis (trifluoromethanesulfonyl) imide at elevated temperatures based on the potentiodynamic polarizations for vessels and pipes that are applicable in solar power plants showed the fundamental role that temperature plays in the corrosion rate [20]. In another study, the corrosion resistance of austenitic stainless steel, carbon steel, nickel-based alloy C22, brass, copper and aluminum alloy ($AlMg_3$) was investigated using the rotating cage method in seven different imidazolium- and ammonium-based ionic liquids up to 90 °C [21]. Stainless steel 304 showed the highest corrosion resistance in water-free and water-diluted ionic liquids at ambient and elevated temperatures, whereas brass and copper faced severe corrosion problems in the studied ionic liquids [21]. Further, the corrosion behavior of mild steel was evaluated as a function of the alkyl chain length in the cation of 1−alkyl-3-methylimidazolium tricyanomethanide ([$C_n$mim] TCM, $n = 2, 4, 6$) ionic liquids for CO_2 capture applications. The immersion test was used at 70 °C and 80 °C, and the results showed that the rate of corrosion decreased with an increase in the cation alkyl chain length [22]. Furthermore, the surface corrosion of different materials (Inconel, bronze, and carbon steel) was studied in 1-butyl-3-methylimidazolium bis (trifluoromethylsulfonyl) imide after a 20-day immersion test at 225 °C. The result showed the formation of corrosion layers was due primarily to the decomposition product of ionic liquids. However, absorption of decomposed products on the surface of alloys restrained the surface corrosion [23].

Although several previous studies have investigated the corrosion behavior of alloys in ionic liquids for different applications, none of them have studied the application of ionic liquids in pneumatic and hydraulic industries at elevated temperatures. This is the basis of this study, which is new, and is the contribution of the present investigation. In the present work, we studied the compatibility of alloys as construction materials in ionic liquid hydrogen compressor at 80 °C. The corrosion behavior of alloys that are in contact with ionic liquids was investigated, and the role of parameters, such as temperature, viscosity, ionic liquid cation and anion, and ionic liquid water absorption, were discussed in detail.

2. Experimental part

2.1. Materials and electrode preparation

We have used the five following ionic liquids (provided by Iolitec [24]) in our study:

1-ethyl-3-methylimidazolium triflate ([EMIM][CF_3SO_3])
1-ethyl-3-methylimidazolium bis (trifluoromethylsulfonyl) imide ([EMIM][Tf_2N]
trihexyltetradecylphosphonium bis (trifluoromethylsulfonyl) imide ([P_{66614}][Tf_2N])
butyltrimethylammonium bis (trifluoromethylsulfonyl) imide ([N_{1114}][Tf_2N]) methyltrioctylammonium bis (trifluoromethylsulfonyl) imide ([N_{1888}][Tf_2N])

The ionic liquids were specifically selected based on certain criteria, such as high thermal and chemical stability, low compressibility, low hydrogen solubility, desired viscosity, and appropriate lubricating properties. The three selected ionic liquids with significantly lower viscosities at 25 °C, which are shown in Table 2 ([EMIM][CF_3SO_3], [EMIM][Tf_2N]), [N_{1114}][Tf_2N]), can be used as replacements for a solid piston in reciprocating compressors, whereas the other two ([P_{66614}][Tf_2N] and [N_{1888}][Tf_2N]) may be more applicable for lubrication purposes. However, the presented ionic liquids and recommended construction material are not limited to ionic liquid hydrogen compressor but can be used for other hydraulic and pneumatic applications such as pumps and compressors for which heat absorption and temperature enhancement of ionic liquids may be of concern. The information regarding the chemical formulae and impurities of selected ionic liquids is summarized in Table 1.

Table 2 shows the dynamic viscosity of the tested ionic liquids at 25 °C and 80 °C and at atmospheric pressure.