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Influencing factors of water electrolysis electrical efficiency

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ABSTRACT

As a promising method of hydrogen production by utilizing renewable energy sources for future, water electrolysis is one of the favorite fields of the study and scientific experiment for many researchers all around the world. One of the most popular related research areas is the efficiency enhancement of the process by the means of reducing the electric power consumption in electrolysers. Regarding to different effective factors related to this issue, many efforts have been done to reach elevated levels of current densities by maintaining or even reducing the electrolysis cell voltage. According to this matter, recommendations could be given for reaching higher process efficiencies. This paper analyzes the factors with an influence on water electrolysis efficiency by studying available verified information in the electrical, electrochemical, chemical, thermodynamics and fluid mechanics fields.

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1. Introduction

Hydrogen production by the means of water electrolysis has been studied for a long time [1,2]. Some available records show that hydrogen has been used by man as an alternative substance in many different fields such as commercial, military and industrial sectors since the late 19th century [3]. Nowadays, only 4–5% [4,5] of total global production of this most abundant substance of the universe [6,7] is being done by water electrolysis. As the water molecule has a very much stable structure in ambient temperature, the required energy to decompose it via electrolysis is relatively high [8]. The most deficiency of the commercial and industrial grade electrolysis systems is their expensive gas production costs. Electricity power demand expense constitutes the largest fraction [9] of hydrogen production costs by using electrolysis method. In industrial electrolysis devices, a large current density is used to break the water molecules into hydrogen and oxygen. The overall equation of this reaction is noted as below:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

The required voltage for splitting a molecule of water is approximately 1.23 V in laboratory conditions which is also called the equilibrium voltage. However, in practical electrolysis cells, higher voltage is required. This matter is caused by overpotential level

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of the electrochemical reaction [10]. The value of overpotential is affected by many different factors, which are going to be discussed in the next sections of this paper. By following the Ohm's law Eq. (2) and the electric power Eq. (3):

$$U = RI \tag{2}$$

$$P = UI \tag{3}$$

where U is the electrical potential in volts, I is the electric current in Amperes, R is the electrical resistance in Ohms and P is the electric power in Watts. It is obvious that in massive current level electrolysers, any slight increase in the cell voltage could increase extra hundreds or even thousands of Watts in system power demand and consumption because the deal is with low voltage and high current levels.

Massive current densities cause a remarkable ohmic potential drop between the electrodes and as a result, higher electrical power loss and less process efficiency are inevitable. Many efforts have been done in order to reduce the required applied voltage. The main causes of the above-mentioned overvoltage and suggested methods to reduce their effect are introduced and discussed as below.

2. Factors with an influence on electrical efficiency

2.1. Electrolyte quality

As it is known, the bases and acids which are used to change the nonconductive nature of pure water have a great effect on the required voltage to drive an electrolytic bath on a certain current density [11,12]. This fact is a result of the ionic conductivity quality of an electrolyte. On the other hand, corrosive nature of these materials, limit the use of very high concentrated acidic and alkali electrolytes in industrial electrolysers where it has negative effects on the life time of electrodes and some other compartments of the system. Considering the mentioned matters, 25–30% KOH solution in water has been widely used in electrolysers for a long time [13].

It is known that the electrocatalytic performance of today's common electrolysis cells is limited [14,15]. This limitation causes efficiency reduction as the overall electrical resistance of the system is affected by the mentioned parameter. Therefore, replacements such as ionic liquids are recently introduced to improve the conductivity and stability factors of electrolytic solutions [16,17]. de Souza et al. [18] performed a research on using an ionic liquid sample of 1-butyl-3-methyl-imidazolium-tetrafluoroborate (BMI.BF4) [19] in water as an electrolyte solution (which is treated as an inexpensive material) in ambient temperature using some easily found electrode materials such as carbon steel (CS), nickel (Ni), nickel–molybdenum (Ni–Mo) alloy and molybdenum (Mo). An efficiency rate of 96% was recorded by some researchers in the case of using low carbon steel electrodes [20] in 10 vol.% of MBI.MF4. This experiment has been done under a current density value of 44 mA cm^{-2}. The recorded efficiency is larger than those of today's commercial and industrial grade electrolysers which are usually less than 73% [21]. However, it should be considered that most of such electrolysers run under much higher current densities than this experimental value.

In addition to the above-mentioned, existence of impurities has some other effects in order to reduce the efficiency and conducting side reactions [22] as well. Magnesium or some other ionic contaminations such as chloride or calcium ions could be expressed as examples of these materials. Moreover, contaminations could block and passivate the electrodes and/or the membrane surfaces [11,23] which sabotages the mass and electron transfer. The latter indeed, is another cause of the ohmic resistance increase in the electric current path.

2.2. Temperature

Temperature is known as one of the most effective variables on the electric power demand of an electrolysis apparatus. Electrolysis is more efficient in higher temperatures [20]. This behavior could be discussed according to the thermodynamic characteristics of a water molecule, where its splitting reaction potential is known to reduce as the temperature increases. In addition, surface reaction and ionic conductivity of an electrolyte are expected to be raised with temperature [24]. Performing the electrolysis process in higher temperatures showed a lower amount of the applied voltage requirement in order to reach same levels of current density [25,26]. This fact has been known and studied for a few decades. Bailleux [27] monitored the operation of a test hydrogen production plant for two years. As it would be predictable, technology of the plant was much simpler back in early 1980s in contrast with today. The report shows that the plant ran on 40 wt% potassium hydroxide alkaline solution, pressure level of 20 bar, current density of 10 kA m^{-2} and temperature range of 120–160 °C. Proper data scanners were used to monitor the current density, voltage, temperature, pressure and gas purity. The latter was required in order to calculate unwanted gas contents of each oxygen and hydrogen outlet. The research reported a 120 mV reduction in the required voltage as the temperature raised from 120 °C to 150 °C. In contrast with this achievement, this report clearly mentions some sorts of "stability problems" such as cracks and gasket leaks, which were caused by system temperature and pressure.

In most of the recent researches, high temperature electrolysis aim much higher temperature ranges. As an example of such sort of experiments, the research results of Fu et al. [28] who have analyzed the thermodynamic aspects of a high temperature steam electrolyser could be mentioned. This experiment was conducted to analyze electrochemical behavior and thermodynamic characteristics of a high temperature steam electrolyser (HTSE) in order to study its efficiency. The research outcome stated clearly that water electrolysis in high temperatures requires less energy than the conventional low temperature electrolysis process. Moreover, efficiency of high temperature electrolysis is at higher levels in analogy with those of low temperature processes. Authors of the above-mentioned paper divided the efficiency of an electrolysis process into three individual parameters: electrical efficiency, electrolysis efficiency and thermal efficiency. They calculated the share of each one of them in overall efficiency were 70%, 22% and 8%, respectively. An increase in the temperature of the process showed a raise level in the share of thermal efficiency in the overall as the electrical efficiency decreased gradually. In this case, electrolysis efficiency almost did not change. The report also covered the results of coupling the HTSE with a high temperature gas cooled reactor (HTGR). When the electrolysis temperature was increased up to 1000 °C, the overall process efficiency changed from 33% to 59%, which is claimed to be over two times more than the efficiency of a conventional alkaline water electrolyser in the same time and made by similar technology.

Moreover, Ganley [29] studied the electrolysis process efficiency of a high temperature and pressure electrolyte (steam). A chemical resistant cell was used to carry out this experiment as the sample electrolyte was a high concentration KOH solution heated up to 400 °C and compressed to different extents. The electrolyte concentration sat to be 19 M at the starting phase of each test, which is, highly corrosive to many metals and alloys. The other variable was the electrodes material which will be discussed in Section 2.5. Results of conducting the experiments at the atmospheric pressure and different temperature levels between 200 °C and 400 °C showed an acceptable fall in the amount of required applied voltage in the case of targeting any given current density. Outcome graphs showed that in the experimental electrolysis apparatus