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FUNDAMENTALS AND USE OF HYDROGEN AS A FUEL

V. K. Singh[1] and N.S. Chauhan[2]
[1]Research Scholar (AHEC), IIT Roorkee, Email id: vineetk.me@gmail.com
[2]Asstt. Prof. of Automobile Engineering Department), RJIT BSF Academy Tekanpur, Gwalior
Email id: er_nehasingh01@yahoo.com

ABSTRACT

Hydrogen has the potential to be an attractive alternative energy carrier for future fuel needs. The use of hydrogen as a fuel requires development in several industry segments, including production, delivery, storage, and end use. Fundamental to the creation of a hydrogen economy is a viable, safe, and affordable hydrogen energy system. The energy end-use applications of hydrogen include stationary, transportation, and portable devices. Hydrogen, when compared to gasoline is more flammable, explosive, buoyant, and diffusive. Hydrogen is the lightest of the elements, with a very low density per unit volume that is approximately 14-fold less than air. Owing to its lightness, there are problems with storage and transport of hydrogen. Various hydride-based storage, carbon materials, and compressed gas storage for automotive applications are being developed.

Keywords: - Hydrogen, gasoline, flammable, diffusive, carbon material..

I. INTRODUCTION

The two most important environmental hazards faced by humankind today are air pollution and global warming. Both have a direct link with our current overdependence on fossil fuels. Pollutants produced from combustion of hydrocarbons now cause even more health problems due to the urbanization of world population. The net increase in environmental carbon dioxide from combustion is a suspect cause for global warming, which is endangering the Earth—the only known place to support human life. In addition, the import of expensive hydrocarbon fuel has become a heavy burden on many countries, causing political and economic unrest. If we look at the past 2000 years' history of fuels, usage has consistently moved in the direction of a cleaner fuel: wood → coal → petroleum → propane → methane. With time, the fuel molecule has become smaller, leaner in carbon, and richer in hydrogen. The last major move was to methane, which is a much cleaner burn than gasoline. Our future move is expected to be to hydrogen, which has the potential to solve both the environmental hazards faced by humankind. Through its reaction with oxygen, hydrogen intensely releases energy in combustion engines or quietly releases it in fuel cells to produce water as its only by-product. There is no emission of smoke, CO, CO_2, NO_x, SO_x, or O3. In fact, the health costs for urban populations can be reduced by switching to hydrogen automobiles. Hydrogen can be produced from water using a variety of energy sources including solar, wind, nuclear, biomass, petroleum, natural gas, and coal. Since renewable energy sources (solar, wind, and/or biomass) are available in all parts of the world, all countries will have access to hydrogen fuel. Hence, a greater democratization of energy resources will occur. Also the use of solar, wind, or biomass in producing hydrogen does not add to environmental CO_2. Before wide scale use of hydrogen fuel can be accomplished, key technological challenges need to be resolved, including cost-effective production and storage of hydrogen. During the early adoption of hydrogen fuel, government incentives will be needed, which may be recovered from savings in the health care expenditures and carbon credits.

II. PHYSICAL PROPERTIES

Hydrogen atom is the lightest element, with its most common isotope consisting of only one proton and one electron. Hydrogen atoms readily form H_2 molecules, which are smaller in size when compared to most other molecules. The molecular form, simply referred to as hydrogen is colorless, odorless, and tasteless and is about

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14 times lighter than air, and diffuses faster than any other gas. On cooling, hydrogen condenses to liquid at −253°C and to solid at −259°C. The physical properties of hydrogen are summarized in Table 1.2. Ordinary hydrogen has a density of 0.09 kg/m^3. Hence, it is the lightest substance known with buoyancy in air of 1.2 kg/m^3. Solid metallic hydrogen has a greater electrical conductivity than any other solid elements. Also, the gaseous hydrogen has one of the highest heat capacity (14.4 kJ/kg K). The hydrogen atom (H) consists of a nucleus of unit positive charge and a single electron. It has an atomic number of 1 and an atomic weight of 1.00797. This element is a major constituent of water and all organic matters, and is widely distributed not only on the earth but also throughout the Universe. There are three isotopes of hydrogen: (1) protium—mass 1, makes up 99.98% of the natural element; (2) deuterium—mass 2, makes up about 0.02%; and (3) tritium—mass 3, occurs in extremely small amounts in nature, but may be produced artificially by various nuclear reactions. The ionization potential of hydrogen atom is 13.54 V. Hydrogen is a mixture of ortho- and para-hydrogen in equilibrium, distinguished by the relative rotation of the nuclear spin of the individual atoms in the molecule. Molecules with spins in the same direction (parallel) are termed ortho-hydrogen and those in the opposite direction as para-hydrogen. These two molecular forms have slightly different physical properties but have equivalent chemical properties. At an ambient temperature, the normal hydrogen contains 75% ortho-hydrogen and 25% para-hydrogen. The ortho-to-para conversion is associated with the release of heat. For example, at 20 K, a heat of 703 kJ/kg is released for ortho-to-para conversion. The conversion is slow but occurs at a finite rate (taking several days to complete) and continues even in the solid state. Catalysts can be used to accelerate the conversion for the production of liquid hydrogen, which is more than 95% para-hydrogen.

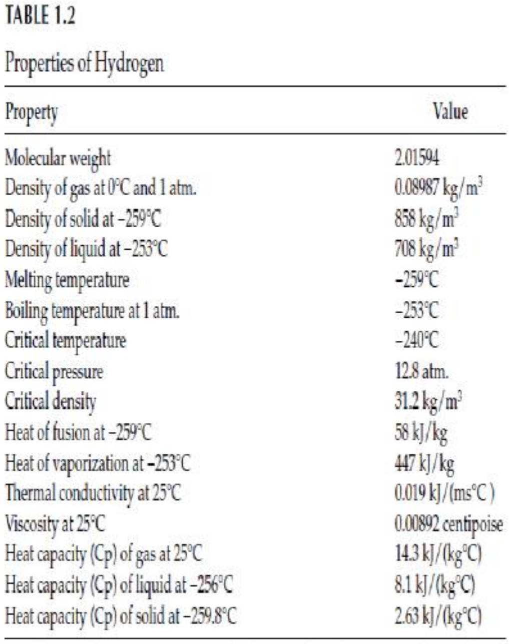

TABLE 1.2

Properties of Hydrogen

Property	Value
Molecular weight	2.01594
Density of gas at 0°C and 1 atm.	0.08987 kg/m^3
Density of solid at −259°C	858 kg/m^3
Density of liquid at −253°C	708 kg/m^3
Melting temperature	−259°C
Boiling temperature at 1 atm.	−253°C
Critical temperature	−240°C
Critical pressure	12.8 atm.
Critical density	31.2 kg/m^3
Heat of fusion at −259°C	58 kJ/kg
Heat of vaporization at −253°C	447 kJ/kg
Thermal conductivity at 25°C	0.019 kJ/(ms°C)
Viscosity at 25°C	0.00892 centipoise
Heat capacity (Cp) of gas at 25°C	14.3 kJ/(kg°C)
Heat capacity (Cp) of liquid at −256°C	8.1 kJ/(kg°C)
Heat capacity (Cp) of solid at −259.8°C	2.63 kJ/(kg°C)

III. CHEMICAL PROPERTIES

At ordinary temperatures, hydrogen is comparatively nonreactive unless it has been activated in some manner. On the contrary, hydrogen atom is chemically very reactive, and that is why it is not found chemically free in nature. In fact, very high temperatures are needed to dissociate molecular hydrogen into atomic hydrogen. For example, even at 5000 K, about 5% of the hydrogen remains undissociated. In nature, mostly the hydrogen is bound to either oxygen or carbon atoms. Hence, to obtain hydrogen from natural compounds, energy expenditure is needed. Therefore, hydrogen must be considered as an energy carrier—a means to store and transmit energy derived from a primary energy source. Atomic hydrogen is a powerful reducing agent, even at room temperature. For example, it reacts with the oxides and chlorides of many metals, including silver, copper, lead, bismuth, and mercury, to produce the free metals. It reduces some salts, such as nitrates, nitrites, and cyanides of sodium and potassium, to the metallic state. It reacts with a number of elements, both metals and nonmetals, to yield hydrides such as NH_3, NaH, KH, and PH_3. Sulfur forms a number of hydrides; the simplest is H_2S. Combining with oxygen, atomic 8 Hydrogen Fuel: Production, Transport, and Storage hydrogen yields hydrogen peroxide, H_2O_2. With

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organic compounds, atomic hydrogen reacts to produce a complex mixture of products; for example, on reacting with ethylene, atomic hydrogen produces C_2H_6 and C_4H_{10}. Hydrogen reacts violently with oxidizers like nitrous oxide, halogens (especially with fluorine and chlorine), and unsaturated hydrocarbons (e.g., acetylene) with intense exothermic heat. When hydrogen reacts with oxygen in either a combustion or electrochemical conversion process to generate energy, the resulting reaction product is water vapor. At room temperature this reaction is immeasurably slow, but is accelerated by catalysts, such as platinum, or by an electric spark. From the safety point of view, the following are the most important properties of hydrogen when compared to other conventional fuels: Diffusion. Hydrogen diffuses through air much more rapidly than other gaseous fuels. With a diffusion coefficient in air of 61 cm^2/s, the rapid dispersion rate of hydrogen is its greatest safety asset. Buoyancy. Hydrogen would rise more rapidly than methane (density at standard condition is 1.32 kg/m^3), propane (4.23 kg/m^3), or gasoline vapor (5.82 kg/m^3). Color, odor, taste, and toxicity. Hydrogen is colorless, odorless, tasteless, and nontoxic; similar to methane. Flammability. Flammability of hydrogen is a function of concentration level and is much greater than that of methane or other fuels. Hydrogen burns with a low visibility flame. The flammability limits of mixtures of hydrogen with air, oxygen, or other oxidizers depend on the ignition energy, temperature, pressure, presence of diluents, and size and configuration of the equipment, facility, or apparatus. Such a mixture may be diluted with either of its constituents until its concentration shifts below the lower flammability limit (LFL) or above the upper flammability limit (UFL). The limit of flammability of hydrogen in air at ambient condition is 4–75%, methane in air is 4.3–15 vol%, and gasoline in air is 1.4–7.6 vol%. Ignition energy. When its concentration is in the flammability range, hydrogen can be ignited by a very small amount of energy due to its low ignition energy of 0.02 mJ as compared to 0.24 mJ for gasoline and 0.28 mJ for methane, at stoichiometry. Detonation level. Hydrogen is detonable over a wide range of concentrations when confined. However, it is difficult to detonate if unconfined, similar to other conventional fuels. Flame velocity. Hydrogen has a faster flame velocity (1.85 m/s) than other fuels (gasoline vapor—0.42 m/s; methane—0.38 m/s). Flame temperature. The hydrogen–air flame is hotter than methane–air flame and cooler than gasoline at stoichiometric conditions (2207°C compared to 1917°C for methane and 2307°C for gasoline).

IV. FUEL PROPERTIES

Hydrogen is highly flammable over a wide range of temperature and concentration. Although its combustion efficiency is truly outstanding and welcomed as a fuel of the choice for the future, it inevitably renders several nontrivial technological challenges, such as safety in production, storage, and transportation. On reacting with oxygen, hydrogen releases energy explosively in combustion engines or quietly in fuel cells to produce water as its only by-product. Unlike ready for fuel use coal or hydrocarbons, hydrogen is not available on the earth. It is, however, available as chemical compounds of oxygen and carbon. For example, hydrogen is present in water; fossil hydrocarbons such as coal, petroleum, natural gas; and biomass such as carbohydrates, protein, and cellulose. Hydrogen has both similarities and differences when compared to the conventional fuels such as methane (natural gas), liquefied petroleum gases (LPG), and liquid fuels such as gasoline. The technical and economic challenges of implementing a “hydrogen economy” require a solution to the fundamental problem of renewable energy production. There are many concerns to be addressed before hydrogen can serve as a universal energy medium, which includes difficulties with hydrogen production, transportation, storage, distribution, and end use.

Hydrogen has the highest energy content per unit mass of any fuel. For example, on a weight basis, hydrogen has nearly three times the energy content of gasoline (140.4 MJ/kg versus 48.6 MJ/kg). However, on a volume basis the situation is reversed: 8,491 MJ/m^3 for liquid hydrogen versus 31,150 MJ/m^3 for gasoline. The low volumetric density of hydrogen results in storage problem, especially for automotive applications. A large container is needed to store enough hydrogen for an adequate driving range. The energy density of hydrogen is also affected by the physical nature of the fuel, whether the fuel is stored as a liquid or as a gas. One of the important and attractive features of hydrogen is its electrochemical property, which can be utilized in a fuel cell. At present, H_2/O_2 fuel cells are available operating at an efficiency of 50–60% with a lifetime of up to 3000 h. The current output range from 440 to 1720 A/m^2 of the electrode surface, which can give a power output ranging from 50 to 2500 W.

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V. HYDROGEN FUEL CELLS

Fuel cells convert the chemical energy of hydrogen directly into electrical and thermal energies. A fuel cell consists of two electrodes: the cathode (positive) and the anode (negative) connected by an electrolyte. Hydrogen and oxygen flow to the anode and cathode, respectively, giving an overall electrochemical reaction $H_2 + 1/2\ O_2 \rightarrow H_2O$ with a theoretical electrochemical potential of 1.23 V (0.40 Hydrogen + 0.83 Oxygen). The electrodes serve two roles: (1) provide electron conduction and (2) provide the necessary surface for the initial deposition of the molecules into atomic species (e.g., electro catalysts that reduce activation energy) before electron transfer. To get higher voltage, the individual fuel cells are combined into a fuel cell "stack," which is done efficiently by connecting each cell to the next in a way that avoids the current being taken off the edge of the electrode, but over the whole surface on the electrode. A bipolar plate is used to interconnect the cell. The continuous operation of the stack requires effective heat, air, hydrogen, and water management, enabled by auxiliary equipment such as pumps, blowers, and controls.

VI. SUPPLY OF HYDROGEN

The important aspect of the hydrogen economy is the production of hydrogen and the total energy consumed and CO_2 emitted in the process. Current world hydrogen production is approximately 50 million t per year, which is equivalent to only 2% of world energy demand. Hydrogen can be produced from a diversity of energy resources using a variety of process technologies. The worldwide consumption of the energy is divided as 38.1% in electricity, 44.3% in heating and industries, and 17.6% in transport, excluding electricity vehicles. About 10% of the electricity generated is lost during distribution, which represents about 4.2% loss in the total primary energy. The worldwide primary energy during the year 2004 was 11.7 gigatons of oil equivalent (Gtoe) or 125,000 TWh, which is equivalent to 496 quad. The consumption is expected to increase to more than 25 Gtoe/year by 2050. Considering the linear extrapolations of the rate of growth of oil consumption and the rate of increase of known oil reserves, it can be deduced that the end of the petroleum supply will probably take place around 2050. Hydrogen-based energy supply can be envisioned to meet the extra demand, the traditional electricity network will be partially fed with natural gas and coal as it is done nowadays, although their percentage contribution will decrease. These fuels will be transformed in cogeneration thermal plants to produce H_2 and electricity with CO_2 sequestration, for instance, using integrated gasification in combined cycle (IGCC) plants provided with CO_2 separation systems (sorbents, membranes, etc.). The concept of high-capacity power plants based on coal will be maintained since this fuel is not appropriate for energy generation (electricity or hydrogen) at a smaller scale. These power plants will also be suitable for the processing of energetic biomass, either alone or in combination with coal. This biomass will be mainly made up of the short-rotation crops and organic wastes that are not destined to be employed in the reformers or biorefineries for the production of hydrogen and befoul, to supply hydrogen to areas far from the general network it will be necessary to build refueling stations. Most of the supply will be provided by a network of refueling stations in which hydrogen will be supplied by a piping system connected to large-scale production plants. These H_2 production plants will use a mix of the primary energy sources most suited to each region.

VII. COST OF HYDROGEN PRODUCTION

Hydrogen can be produced in a number of ways depending on the feedstock as described earlier. In addition, the design of a hydrogen energy system is site specific, depending on the type of demand, the local energy prices (for natural gas, coal, electricity, etc.), and the availability of primary energy resources. A typical cost analysis for hydrogen production and distribution from different feedstocks. The cost estimation is based on the fact that the energy content of a gallon of gasoline and a kilogram of hydrogen are approximately equal on a lower heating value basis. Thus, a kilogram of hydrogen is approximately equal to a gallon of gasoline equivalent (gge) on an energy content basis. The cost of producing hydrogen varies significantly by the type of technology and distribution channel used. According to an analysis in the year 2004, the total cost of hydrogen ranged from $1.91 to 6.58/kg for hydrogen made from coal and shipped by pipeline and for hydrogen made on-site from electrolysis.

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It is estimated that by the year 2040, approximately 150 million t of hydrogen will be required annually. To meet this demand solely from natural gas, approximately 0.43 million m^3 of natural gas per year of 777,000 facilities would be required, which would cost roughly 1 trillion dollars. If the demand is solely met by nuclear energy, it would require 240,000 t of unenriched uranium and about 2000, 600 MW power plants, which would cost $840 billion. In the case of solar energy, 113 million, 40 kW systems with 2500 kWh of sun/m2 will be required, which will cost $22 trillion. In the case of wind energy, 1 million, 2 MW turbines using an average wind speed of 7 m/s would be required, which will cost $3 trillion. In the case of biomass, 1.5 billion t of dry biomass would be required, which will need 113.4 million acres of farm land, and then to produce hydrogen approximately 3300 plants will be needed, which will cost $565 billion to build. Similarly, coal scenario will demand 1 billion ton per year of coal, and approximately 1000, 275 MW coal gasification/steam reformation plants, which will cost about $500 billion.

VIII. HYDROGEN STORAGE

One of the most critical factors in inducting hydrogen economy is transportation and on-vehicle storage of hydrogen. Storing hydrogen that flexibly links its production and final use are key element of the hydrogen fuel utilization. The major contribution to the problem is from low gas density of hydrogen. For example, to store energy equivalent to one gasoline tank, an ambient pressure hydrogen gas tank would be more than 3000-fold the volume of the gasoline tank. Summarizes the weight requirements for various on-board hydrogen storage options; here 5 gal. of the gasoline has been taken as a reference, which is sufficient for a vehicle to drive up to a distance of 300 mi.

IX. CURRENT CHALLENGES

The main obstacle in the utilization of hydrogen fuel in the automobiles is due to its low density. Even when the fuel is stored as a liquid in a cryogenic tank or in a pressurized tank as a gas, the amount of energy that can be stored in the space available is limited, and hydrogen cars, therefore, have a limited range compared to their conventional counterparts. Hence, storing hydrogen on board for 500 km driving range is a major challenge while meeting the performance (weight, volume, kinetics, etc.), safety, and cost requirements without compromising on passenger or cargo space. The fuel storage systems in today’s gasoline vehicles have an energy density of about 6 kWh/L. With the improved fuel economy of a hydrogen fuel-based vehicle and a conformable hydrogen storage system, the requirement for a fuel cell vehicle is 2.7 kWh/L, which is higher than liquid hydrogen (20 K, 1 bar). The second major problem is the high cost of making reliable fuel cells. A combination of the two problems is hindering the development of hydrogen automobiles. Also, the existing hydrogen dispensers are not adequate to support commercial fueling. Cost, reliability, and safety must be significantly improved to allow commercial fueling. Fuel cells have operating advantages for both stationary and mobile applications in that they are quiet and typically have high efficiency at partial loads. The direct conversion of the energy stored in the fuel to electricity in a fuel cell can be achieved at high efficiencies, avoiding limitations of standard heat-to-power cycles used in combustion engines and turbines. The higher efficiency of fuel cells (approximately 60%) compared to gasoline (22%) and diesel (45%) internal combustion engines would substantially help in the future energy needs. However, fundamental performance problem remain to be solved before hydrogen fuel cells can compete with gasoline. A primary factor limiting PEMFC performance is the slow kinetics of the oxygen reduction reaction at the cathode. Even with the most effective platinum-based catalysts, the slow reaction reduces the voltage output of the fuel cell from the ideal 1.23–0.8 V or less when practical currents are drawn.

The solutions for speeding up the reaction are hidden in the complex reaction pathways and intermediate steps of the oxygen reduction reaction. The role of different key features as the atomic configuration of catalysts and their supports, and the electronic structure of surface reconstructed atoms and adsorbed intermediate species, is within reach of fundamental understanding.

X. FUTURE OUTLOOK

The hydrogen economy has both societal and technical appeals as a potential solution to provide abundant supply with minimal environmental impact. The success of a hydrogen economy will depend on the technological solution of the remaining storage and production issues. The investment requirements in research and development are high, and the outcome for specific, promising approaches is uncertain. The acceptance of hydrogen fuel depends not only on its practical and commercial appeal, but also on its record of safety in widespread use. The flamiability, buoyancy, and permeability of hydrogen may present challenges to its safe handling that are different from, but not too difficult than those of other energy carriers. Also, a key to public acceptance of hydrogen is the development of safety standards and practices that are well known and routinely used. The success of hydrogen economy will definitely depend on new energy sources and new energy converters. Bringing hydrogen and its energy conversion partner (e.g., fuel cells) to the hydrocarbon energy system level is a fascinating challenge, especially with the development of infrastructure. Today, the technologies for producing, storing, and distributing hydrogen are well known and widely used in the chemical industry. Also, the technical building blocks for future hydrogen fuel system are well documented. Hydrogen end-use technologies such as fuel cells, hydrogen vehicles, power, and heating devices are undergoing rapid development. Still the costs and time factors inherent in changing the present energy system mean that building a large-scale hydrogen fuel infrastructure will take a long time. The development of hydrogen end-use systems, such as fuel cells, and their penetration into transportation or power markets will determine the pace of introducing hydrogen fuel. Because hydrogen can be produced from a variety of sources, a future hydrogen fuel infrastructure could evolve in a variety of ways. As demand increases and becomes more geographically dense, centralized production with local pipeline distribution would become more economically attractive. Once a large, geographically concentrated demand evolves, carbon sequestration can be incorporated. A variety of low or zero net-carbon emitting sources of hydrogen may be utilized at this time. The development of such a market will depend on the political will to move toward a zero-emission energy system and on the relative economics of hydrogen versus other low-polluting alternative fuels.

XI. CONCLUSIONS

Hydrogen has the potential to be an attractive alternative energy carrier for future fuel needs. The use of hydrogen as a fuel requires development in several industry segments, including production, delivery, storage, and end use. Fundamental to the creation of a hydrogen economy is a viable, safe, and affordable hydrogen energy system. The energy end-use applications of hydrogen include stationary, transportation, and portable devices. Hydrogen can be produced from a variety of feedstocks including natural gas, coal, biomass, wastes, solar, wind, or nuclear. Hence, the participation in hydrogen economy will be much more open than the present energy industry limited to countries with petroleum or coal reserves. In addition, the production of hydrogen from renewable sources, or from fossil fuel with carbon sequestration, does not emit greenhouse gases. Owing to the differences in the properties, risks associated with hydrogen are different from conventional fuels. Hydrogen is a colorless, odorless, tasteless, and nontoxic gas.

Hydrogen, when compared to gasoline is more flammable, explosive, buoyant, and diffusive. Hydrogen is the lightest of the elements, with a very low density per unit volume that is approximately 14-fold less than air. Owing to its lightness, there are problems with storage and transport of hydrogen. Various hydride-based storage, carbon materials, and compressed gas storage for automotive applications are being developed.

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