HYDROGEN ENERGY AND TRANSPORTATION

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Abstract

At the beginning of the twenty-first century, the most important environmental problems are caused by fossil fuels (Coal, petroleum and natural gas). They are causing ozone layer depletion, acid rains, global warming, oil spills and pollution. Their effects include a growing hole in the ozone layer, damage to the forest and farm products by acid rains, increasing global temperatures, melting of the ice caps in the southern and northern polar regions, melting of glaciers, reduction of the snow deposits in mountains, oil slicks caused by tanker accidents and otherwise, and atmospheric air pollution. There is a very elegant answer to these problems. It is the Hydrogen Energy System, which is considered as a replacement of the present day fossil fuel system.

Air pollution is worse in the larger cities of the earth, because of the concentration of industries (which consume coal, fuel oil and other fossil fuels) on one hand, and transportation (cars, buses and trucks), which mainly consumes gasoline and diesel oil. When fossil fuels and hydrogen are compared for suitability as a transportation fuel, hydrogen becomes the fuel to remedy air pollution in the cities and the most suitable fuel for transportation, as well as the fuel to remedy the global environmental problems.

1. INTRODUCTION

The Hydrogen Energy System, or the Hydrogen Economy was formally proposed - as an answer to interrelated global problems of (1) the rapid depletion of fossil fuels and (2) the environment problems caused by their utilization – at The Hydrogen Economy Miami Energy (THEME) Conference, 18-20 March 1974, Miami Beach, Florida, U.S.A. Since then, there have been increasing research efforts to investigate the various aspects of the hydrogen energy system and technologies. Most of the results have been presented in the proceedings of the THEME Conference [1]* and in those of the 13 World Hydrogen Energy Conferences [2-14] held to date. Books and reports by Bockris [15], Veziroglu [16], Ohta [17], Williams [18], Skelton [19], and Winter and Nitsch [20] cover the hydrogen energy system, hydrogen production methods, storage, transportation, and utilization in some depth. Figure 1 shows the Hydrogen Energy System. The following sections will emphasize some recent developments in Hydrogen Energy technologies [21] and a comparison of the fossil fuels and hydrogen for suitability as a transportation fuel.*

2. HYDROGEN PRODUCTION

* numbers in square brackets refer to the references at the end of the paper.

Hydrogen is currently being produced mainly by steam reforming of natural gas, and also by partial oxidation of heavy oil and by coal gasification. Different methods of hydrogen production based on renewable energy sources have been or are being developed. They are direct thermal decomposition or thermolysis, thermochemical processes, electrolysis and photolysis. It appears that so far water electrolysis is the only method developed that can be used for large-scale hydrogen production. Today, available advanced electrolyzers are more than 90% efficient, and research efforts are aimed toward new advanced concepts in electrode design and material improvement in order to reduce the costs, increase reliability, and extend the lifetime. Electrolysis can effectively be used in combination with photovoltaic (PV) cells. The results of an experimental 10-kW PV-electrolysis plant in Germany have indicated a low specific energy consumption (3.84 kWh/Nm^3), good gas purities, fast dynamic response, and a wide range of operation [22]. These results, and the results of other testing facilities, indicate that the PV-electrolysis systems have the potential to become available for large-scale hydrogen production, as well as for individual stand-alone applications. Electrolysis can also be used with hydro, wind, wave, current, tide, and ocean-thermal produced electricity. The concept of a hydro-hydrogen clean energy system is under investigation in a 100-MW, international project [23]. The goal of this investigation is to prove the feasibility of conversion of the Canadian hydropower into hydrogen, the maritime transport of liquid hydrogen or methylcyclohexane to Europe, and the storage, distribution, and end use there. Another successful solar hydrogen production project is the HYSOLAR Project jointly run by Germany and Saudi Arabia [24].

Photolysis, or direct extraction of hydrogen from water using only sunlight as an energy source, can be accomplished by photobiological systems, photochemical assemblies, or photoelectrochemical cells [25]. Intensive research activities open new perspectives for photoconversion, where new redox catalysts, colloidal semiconductors, immobilized enzymes, and selected microorganisms could provide the means of large-scale solar energy harvesting and conversion into hydrogen.

3. HYDROGEN DELIVERY

Hydrogen must be stored to overcome daily and seasonal discrepancies between energy source availability and demand. For large-scale storage, the recommended method is the underground storage of hydrogen in aquifers, depleted petroleum and natural gas fields, and man-made caverns resulting from mining and other activities. The latter method is already successfully utilized in some countries.

In the hydrogen energy system it is envisaged that from the production plants and/or storage, hydrogen will be transported to consumers by means of underground pipelines and/or supertankers [26] To match consumption demand, hydrogen can be regionally transported and distributed, both as a gas and as a liquid, by pipelines or in insulated containers by road and rail transportation. Depending on the end use, hydrogen has to be stored in stationary or mobile storage systems at the consumer end as a pressurized gas, as a liquid, or using some of its unique physicochemical properties, in metal hydrides or in activated carbon. Because of hydrogen's low density, this secondary storage could be a problem, especially where space is limited (eg, in automobiles). For some applications (air and aerospace transportation) hydrogen must be used in liquid form (or even in a form of slush hydrogen, which is a mixture of liquid and solid hydrogen). Since liquefaction of hydrogen occurs at 23 K, large amounts of energy (about 35-40% of its energy content) are required to produce liquid hydrogen and to keep it liquid. Therefore, novel liquefaction methods are being investigated in order to reduce the energy requirements and the cost. It has recently been announced that the engineers and scientists at the Astronautics Technology Center in Madison, Wisconsin, were designing and building a revolutionary magnetic liquefier that is expected to offer higher efficiency than conventional equipment, as well as reduced size and cost [27].

4. HYDROGEN UTILIZATION

Hydrogen as an energy carrier has many possible applications. It can be used instead of fossil fuels for virtually all purposes: as a fuel for surface and air transportation, as a fuel for heat production, and even as a fuel for production of electricity directly (in fuel cells) or indirectly (through gas and steam turbine-driven generators).

Large amount of research work has been done on the use of hydrogen as a fuel for cars, trucks, and buses. They have been mainly aimed toward conversion of the existing internal combustion engines to run on hydrogen (and solving problems related to hydrogen combustion characteristics) and studying the problem of hydrogen storage in vehicles. Two concepts based on liquid hydrogen storage and hydride storage have been developed, tested, and successfully demonstrated [28]. Problems of on-board hydrogen storage can be avoided if engine efficiency is improved. The hydrogen/air fuel cells in conjunction with an electric motor are about two to three times as efficient as internal combustion engines, and do not generate any emissions (except water). They are considered to be ideal for the new generation, zero emission vehicles. Energy Partners, of West Palm Beach, Florida, has already developed and demonstrated a fuel cell powered prototype passenger vehicle [29].

Liquid hydrogen has numerous advantages as a fuel for commercial subsonic and especially for supersonic aircraft [30,31]. In April 1988, the flight of a commercial airliner (Tupolev 155) fueled with liquid hydrogen was demonstrated in the former USSR. The Germans are carrying out preliminary work on a project for a hydrogen-fueled commercial airliner (Airbus) [32]. The former Soviet Union and Germany signed an agreement to jointly develop hydrogen-powered propulsion technology for civilian aircraft [33]. All the aerospace programs, including the U.S. National Aero-Space Program, are based on liquid or slush hydrogen as fuel.

For domestic applications, the Fraunhöfer Institute for Solar Energy Systems, in Germany, has developed, designed, and tested appliances based on the principle of catalytic combustion of hydrogen, which are now deliverable to customers [34]. These appliances are a catalytic hydrogen stove and an absorption refrigerator with catalytic H_2 eliminator systems. Catalytic combustion of hydrogen is advantageous with respect to efficiency and emissions.

Other possible hydrogen applications in homes and commercial buildings are heat (space heating and air conditioning, water heating) and electricity generation. Hydrogen fuel cells are very efficient devices (up to 80% combined electric and thermal efficiencies), which can produce both electricity and heat. The Toshiba Corp. of Japan, jointly with the International Fuel Cells Corp. (IFC) of the United States, is now planning to sell on-site 200-kW fuel cell power plants [35] The 4.5-MW fuel cell plant, designed by United Technologies Corp. for Tokyo Electric Power, has operated flawlessly and to date has logged hundreds of hours at peak power. Another, an 11MW plant, began operating in December 1990 for the same utility company [36].

Efficient hydrogen use in electricity generation will become very important for solar power plants, where hydrogen serves as an energy storage medium. During periods when solar energy availability is higher than energy demand, surplus energy can be used in electrolyzers to produce hydrogen, and during the periods when demand is higher than availability or the sun is not available, electricity can be produced from hydrogen via fuel cells.

The German Aerospace Establishment (DLR) has developed a hydrogen/oxygen steam generator which is extremely efficient (almost 100%), compact, and relatively inexpensive [37]. This steam generator has been developed for spinning reserve in power plants, but it can also be used for peak-load electricity generation in industrial steam supply networks, and as a micro-steam generator in medical technology and biotechnology [28].

5. STANDARDS FOR HYDROGEN ENERGY TECHNOLOGIES

International standards are needed to facilitate the economic and safe production, storage, transport and utilization of hydrogen as an environmentally compatible energy carrier and feedstock and to enable international development and exchange of hydrogen energy technologies. The International Standards Organization (ISO) has established a technical committee (TC-197), which is working on international standards for hydrogen energy technologies [38]. This is a very important activity and will lay the foundations of the Hydrogen Energy System.

6. COMPARISON OF FUELS FOR TRANSPORTATION

Presently, the most widely used transportation fuel is gasoline. Natural gas (Methane) is making inroads in the transportation field, since it is environmentally more compatible than gasoline and is less expensive. On the other hand, hydrogen has certain unique characteristics (such as being environmentally most compatible, having high utilization efficiencies especially in fuel cells, and being the lightest), which makes it a desirable fuel for transportation. However, it also has some drawbacks, such as being bulky and is presently expensive.

In order to compare the above mentioned fuels, Table 1 has been prepared [39-50], which lists their characteristics related to their suitability as a transportation fuel. Higher energy content per unit mass is desirable as it provides the vehicle with more energy for a given mass. Similarly higher energy content per unit volume is desirable, since it provides the vehicle with more energy for a given volume. Obviously, the higher the utilization efficiency, the better the fuel.

Lower density reduces the vehicle weight (i.e., why hydrogen is the fuel of choice for space transportation) and makes the fuel safer, since it increases the buoyancy force for speedy dispersal of the fuel in case of a leak. For the same reason, higher diffusion coefficients are helpful. Higher specific heat causes a fuel to be safer, since it slows down the temperature increases for a given heat input. Wider ignition temperatures make the fuels less safe, as they increase the limits in which a fire could commence. Higher flame temperature, higher explosion energy and higher flame emissivity make a fuel less safe as well, since its fire would be more damaging. For a good fuel, environmental damage caused by its use must be as minimal as possible.

To rank the fuels, as to their suitability for transportation, Table 2 has been prepared using the data presented in Table 1. It ranks the fuels from 1 to 3 for a given property; one being the most desirable fuel and three, the least desirable. In addition to the items given in Table 1, three more pertinent categories have been added, viz., toxicity of fuel, toxicity of combustion products and the cost of fuel. These rankings have been summed up for each fuel in order to arrive at an overall ranking. As can be seen, hydrogen becomes the most desirable fuel, followed by methane and gasoline, in that order.

7. HYDROGEN FUELED VEHICLES

As we have seen in the last section, hydrogen is the most desirable fuel for transportation. Its unique properties make it suitable as a fuel for motive power, both for I.C. engine powered vehicles and electric powered vehicles. In addition to its unsurpassed environmental characteristics, the lean burning property of hydrogen make it a suitable and efficient fuel for the stop and go type of city driving. The Mazda Corporation of Japan has reported that hydrogen is the best fuel for Wänkel engines.

The efficiency advantage of hydrogen fuel cells is being put into use in electric cars in which hydrogen fuel cells provide the motive power, rather than electric batteries. Hydrogen fuel cells can and do overcome the problems encountered with battery powered electric cars, such as small acceleration, low velocity and short driving range. All the major car companies, viz., General motors, Ford, Daimler-Chrysler, BMW, Toyota, Honda and Mazda, are now involved in the development and commercialization of hydrogen fueled motor vehicles. Most of these companies are preparing to offer hydrogen-fueled cars in 2004. Mercedes Bus Division will have a city bus on the market by the year 2003. Many more polluted city transport departments are lining up with orders in order to fight pollution, even though these buses will initially cost about three times more than the diesel buses.

8. CONCLUSIONS

As a result of the foregoing study, it becomes clear that hydrogen is the best fuel with many unique and unmatched qualities. It is the environmentally most compatible fuel, the most efficient fuel and the best transportation fuel. It will provide the planet Earth, the only one known to be hospitable to life, with a clean and sustainable energy system. It is obvious that hydrogen should be the fuel of choice for the post fossil fuel era, when we shall have the option to manufacture the fuel we prefer.

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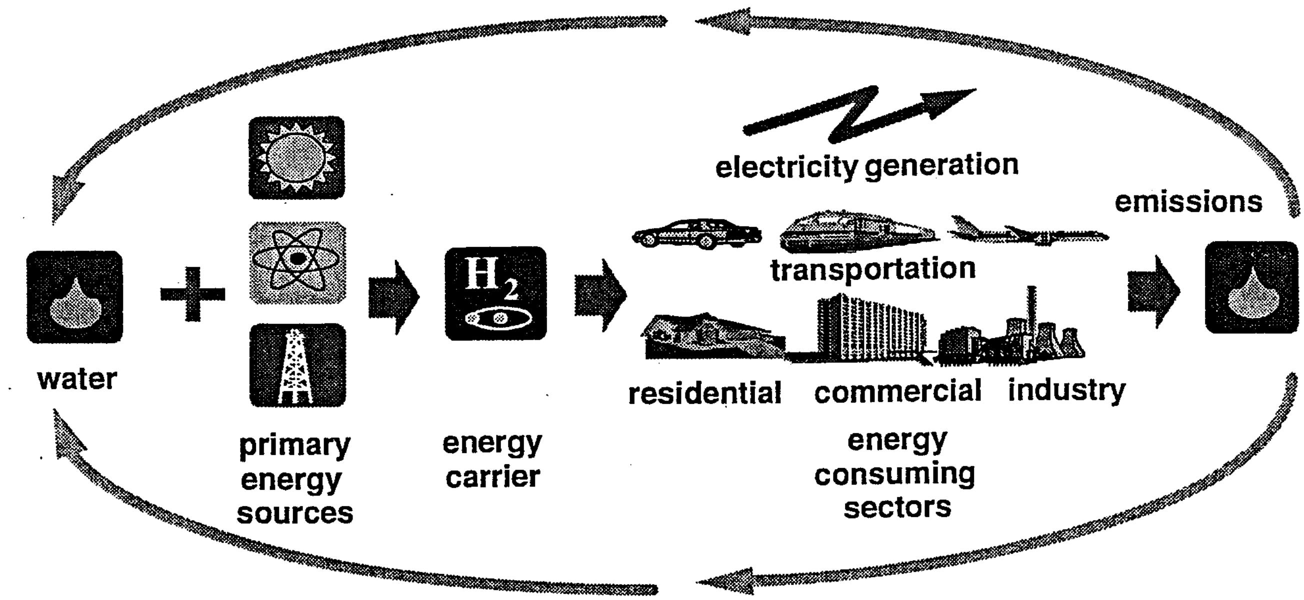
TABLE 1. CHARACTERISTICS RELATED TO SUITABILITY OF FUELS FOR TRANSPORTATION

PROPERTY	GASOLINE	METHANE	HYDROGEN (GASEOUS)
Energy Per Unit Mass (MJ/kg)	47.4	50.0	141.9
Energy Per Unit Volume (GJ/m^3)	34.85	0.04	0.013
Utilization Efficiency (%)	15-25	15-25	50-60 (a) 18-30 (b)
Density (kg/m^3)	4.40	0.65	0.084
Diffusion Coefficient in Air (cm^2/s) (c)	0.05	0.16	0.61
Specific Heat at Constant Pressure (J/gK) (c)	1.20	2.22	14.89
Ignition Limits in Air (vol %)	1.0-7.6	5.3-15.0	4.0-75.0
Igntion Energy in Air (mJ)	0.24	0.29	0.02
Ignition Temperature (^{o} C)	228-471	540	585
Flame Temperature in Air (^{o} C)	2197	1875	2045
Explosion Energy (g TNT/kJ) (d)	0.25	0.19	0.l7
Flame Emissivity (%)	34-42	25-33	17-25
Environmental Damage (2000 $/GJ)	12.54	8.29	0.0 (a) 0.68 (b)

(a) Fuel Cell
(b) I.C. Engine
(c) At Normal Temperature and Pressure
(d) Theoretical Maximum: Actual 10% of Theoretical

TABLE 2. SUITABILITY RANKING OF FUELS FOR TRANSPORTATION

PROPERTY	GASOLINE	METHANE	HYDROGEN (GASEOUS)
Energy Per Unit Mass	3	2	1
Energy Per Unit Volume	1	2	3
Utilization Efficiency	2.5	2.5	1
Density	3	2	1
Diffusion Coefficient in Air	3	2	1
Specific Heat at Constant Pressure	3	2	1
Ignition Limits in Air	1	2	3
Ignition Energy in Air	2	1	3
Ignition Temperature	3	2	1
Flame Temperature in Air	3	1	2
Explosion Energy	3	2	1
Flame Emissivity	3	2	1
Environmental Damage	3	2	1
Toxicity of Fuel	3	2	1
Toxicity of combustion Products	3	2	1
Cost of Fuel	2	1	3
Totals	41.5	29.5	25
Overall Ranking	3	2	1



Figures 1. A Schematic Diagram of the Hydrogen Energy System.