HYDROGEN: CURRENT ISSUES IN TECHNOLOGY AND CHEMISTRY (REVIEW)*

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The technological revolution in developed countries had led to a situation in which hydrogen has now become one of the main intermediates in the chemical industry. During the past 20 yr, hydrogen production throughout the world has almost doubled, reaching 60,000,000 tons in 1988-1989. It is predicted that in the first decades of the next century there will be a further increase of hydrogen production to 75,000,000-80,000,000 tons/yr and, according to some estimates, up to 100,000,000 tons/yr.

Virtually all the hydrogen is being used and, in the foreseeable future, will be used only in chemical technology, i.e., in the production of ammonia, methanol, and synthetic fuels, in advanced petroleum processing, and in the production of high-quality motor fuel. In these branches, from 50 to 200 tons of hydrogen is consumed for every 1000 tons of finished product.

The main process for the production of hydrogen is steam reforming of natural gas and heavy fractions of crude feedstock at 700-800°C. In principle, the production of hydrogen from natural gas is an ecologically "dirty" process because about 8 tons of CO and CO₂ is formed per ton of hydrogen. Nevertheless, according to estimates by specialists in the USA, Japan, and the Federal Republic of Germany (FRG), until 2000 the steam reforming of methane will remain the most economical method, although the cost of the hydrogen produced in this way will depend on world prices for natural gas and electric power.

Until the middle of the 1980s, the production of hydrogen-containing gas from reforming of hydrocarbon feedstock in the USSR and USA remained at approximately the same level, about 5,500,000-6,000,000 tons/yr on the basis of the hydrogen contained in it. The gas mixture obtained by steam reforming of methane contains up to 70-75 vol. % hydrogen. Separation of such gas mixtures and production of enriched technical hydrogen (containing up to 5 vol. % impurities) and pure or high-purity hydrogen (containing less than 0.01 and 10⁻⁶ vol. % impurities, respectively) is an expensive operation, making a significant contribution to the cost of the target product, up to 25-40% in the production of technical hydrogen and up to 85-90% in the production of high-purity hydrogen. In the USSR, these expenses are relatively higher than in the USA, Japan, and other industrially developed countries, which indicates that the processes underlying the recovery of hydrogen from methane-reforming gases are imperfect and that there are significant reserves that can be used to improve both the economic indexes and the ecological indexes of the technology.

The main difference is in how hydrogen-containing gas is used in the USA and in the USSR. In the USA, during the past 10 yr, the share of hydrogen recovered from it almost doubled and reached 35%, but in the USSR it remained at the level of 1980, about 5-6%.

According to estimates by non-Soviet specialists, as of 2000 a significant share in the industrial production of hydrogen-containing gases will be assumed by processes based on the use of solid fossil fuels for steam reduction, especially low-grade coals. Such technologies have great promise because the energy equivalent of the earth's coal reserves is estimated to be sufficient to ensure the needs of the world's economy for 500-700 yr. Intensive scientific-research and design work in this field is now being carried out in countries of the European Economic Community, especially the FRG.

A significant contribution to hydrogen production can be made by technologies for hydrogen recovery from industrial gases from byproduct coking processes containing more than 50 vol. % hydrogen. In the USSR, the production of hydrogen from such gases, just as its re-

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covery from industrial petroleum-processing gases containing from 15 to 70 vol. % hydrogen, has been inadequately implemented, although prior to the beginning of the 1960s more than half of the hydrogen used in the nitrogen industry was produced by recovery from byproduct-coking gases. Also, the USSR has very large resources of so-called "secondary" hydrogen from petroleum-processing and petrochemical processes, which is now burned in flares and in the fuel system; according to very rough estimates, these resources are about 400,000-500,000 tons/yr.

On the average, the share of electrolytically produced hydrogen in the world and in the USSR does not exceed 1-2%, but in the USA, Canada, and some countries of the European Economic Community it is significantly higher and shows a stable tendency to increase further. For development of new uses of hydrogen in chemical technology, materials science, and metallurgy, electrolytically produced hydrogen, despite its relatively higher cost, is preferable because the expenses for its purification are significantly less than for hydrogen obtained by reforming of methane. An additional advantage of electrochemical processes for the production of hydrogen is their ecological acceptability and their nondependence on sources of natural nonrenewable raw materials.

The main tendency of the modern hydrogen-consuming industry is a rapid increase of the share of science-intensive branches, in which, in principle, pure and high-purity hydrogen must be used rather than enriched hydrogen-containing gas. Such branches include metallurgy, in particular, direct reduction of metals from oxides; the electronic industry and semiconductor technology, i.e., high-purity silicon and germanium, films, coatings, and ceramic materials; cryogenic technology, i.e., the production of liquid hydrogen for the development of supersonic transport aviation; and the food and pharmaceutical industry. The need of the USSR's national economy for such hydrogen is estimated to be close to 100,000 tons in 1995 and 150,000-200,000 tons beginning in 2000.

In the middle of the 1970s, a concept of hydrogen energy technology was proposed in which hydrogen was considered as an ecologically acceptable energy source. As an energy source, hydrogen is promising for use in electrochemical energy generators, whose efficiency is 2-2.5 times as great as that of thermal engines. If we digress from the question of the primary source of the energy necessary for the production of hydrogen and regard hydrogen energy technology as a real national-economic issue of the next century, we must see clearly that real progress in this field is impossible until industry is able to produce additionally hundreds of tons of pure hydrogen suitable for oxidation in electrochemical generators. This is possible only with a level of hydrogen-production technologies completely different from today's level. In the USA, Japan, and the FRG, in governmental programs alone, about $50,000,000 is being spent annually on scientific-research and design work for the creation of such technologies.

One of the most promising trends in the creation of basically new technologies for hydrogen production oriented toward the future is the use of solar energy in photochemical, photocatalytic, and photoelectrochemical processes for the decomposition of water. Outside the USSR, the scientific principles of these processes are being intensely developed, and the first such pilot-plant units are predicted for the beginning of the 21st century. The future of hydrogen energy technology as a global energy-technological concept will probably depend greatly on how realistic these predictions turn out to be.

The issues of technology of the current decade are related to the creation of resource-conserving ecologically acceptable processes for the production, concentration, and purification of hydrogen. Above all, these are electrochemical processes, the creation of new-generation electrolyzers for electrolysis of liquid water or water vapor with energy consumptions 4.2-4.3 kWh/nm³ and less than 3.8 kWh/nm³, respectively. At present, in Soviet installations for water electrolysis, the real energy consumption is 5.5-6.0 kWh/nm³ hydrogen, i.e., 25-30% higher than in non-Soviet ones. The basis for progress in applied electrochemistry is the use of new materials with higher functional and technoeconomic characteristics, especially new cathode materials with high corrosion resistance at temperatures about 100°C and high current densities.

The second trend is highly efficient technologies for separation of industrial hydrogen-containing gases from methane reforming and manufacture of pure and high-purity hydrogen.

Three groups of technologies are most promising for the large-scale production of such hydrogen by 2000. For primary enrichment of hydrogen-containing gases and production of 95-