Hydrogen as fuel for turbines and engines

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1 Introduction

1.1 Background
Sydkraft in Sweden and Statkraft in Norway are jointly working with a feasibility study to examine the possibilities for the companies to utilize hydrogen in their future activity.

1.2 Purpose
As a part of the feasibility study this study will give a status report of the technique of today and the future possibilities to use the technique for using hydrogen as fuel in engines, turbines etc. The study is carried out as a literature study.
2 Hydrogen use programs

2.1 WE-NET - World Energy Network

The WE-NET program is a project that has been conducted by the New Energy and Industrial Technology Development Organization (NEDO) since 1993 as part of the Japanese government’s New Sunshine Program. The WE-NET program aims to secure new energy sources and maintain the global environment in good condition by building an international network of hydrogen energy (Figure 2.1). Research and development works have been carrying out since 1993. Over the last years, steady progress has been made and excellent results obtained in R&D activities of each subtask on hydrogen production, transportation, storage, and utilization systems. Besides technology development total system design and analysis have been conducted. The program is being proceeded in cooperation with government, industry and academia [1].

The project is divided in different phases. Phase 1, which consists of nine subtasks, will be completed in March 1999. Phase 2 will be discussed and outlined from the results from phase 1 [2]. In phase 1, it is planned to conduct the necessary surveys and basic and elementary technology research toward establishing the base technology for hydrogen production, hydrogen transport/storage and hydrogen utilization. This is for accumulating the data for the optimal design of the total system and to find the technology basis for the design and construction of a pilot plant [3].

Figure 2.1, The WE-NET Hydrogen Energy System Flow
3 Internal Combustion Engines

3.1 Background

Hydrogen is a very suitable fuel for internal combustion engines (ICE). Hydrogen powered ICEs are on average about 20 per cent more efficient than comparable gasoline engines [4]. The equation below shows the ideal thermal efficiency of an ICE.

\[ \eta = 1 - \left( \frac{1}{r} \right)^{k-1} \]

where:

\( r \) = compression ratio
\( k \) = ratio of specific heats \((C_p/C_v)\)

From this equation you can see that the thermal efficiency can be improved by increasing either compression ratio or the ratio of specific heat. Both these ratios are higher in hydrogen engines than in comparable gasoline engines.

Hydrogen fueled ICE also have some disadvantages compared to gasoline fueled engines. The hydrogen ICE has a higher volume of the stoichiometric mixture, ~30 per cent of the cylinder volume compared to ~2 per cent for the gasoline ICE. Under these conditions, the energy of the hydrogen mixture is only 85% that of the gasoline mixture. This results in a ~15 per cent reduction in power [4]. This mean that the same engine running on hydrogen will have ~15 per cent less power than when running on gasoline but the efficiency will be around 20 per cent higher.

There are some ways to improve the power output. For example by using more advanced fuel injection techniques or liquid hydrogen. If liquid hydrogen is premixed with air, the amount of hydrogen that can be introduced in the combustion cylinder can be increased by ~ one-third.

The low emissions are one of the most important advantages with hydrogen as a fuel for ICE compared to gasoline engines. The only products from hydrogen combustion are water vapor and some nitrogen oxides. The emissions of NOx \((< 10 \text{ ppm})\) are in the range of one magnitude smaller for hydrogen ICE than for gasoline ICE.

3.2 Current status

The use of hydrogen in internal combustion engines (ICE) was demonstrated over 100 years ago. Hydrogen fueled engines offer the potential of no carbon emissions and very low NOx-emissions. This is combined with a high thermal efficiency.

Some problems remain to be solved before a hydrogen fueled internal combustion engine will be competitive and cost effective. These problems are mainly the fuel delivery and practical storage (in cars). A research challenge is to achieve high efficiency and low emissions and overcome the problems of preignition and flashback.
These problems have been common with hydrogen fuel in the past. Flashback is the premature ignition of the fuel and air mixture that occurs when the exhaust valve is open. This problem is more serious with hydrogen than hydrocarbons because of hydrogen’s high flame speed, two to ten times higher than that of hydrocarbons [5], and the low ignition energy of hydrogen. Also, hydrogen has a wide range of flammability in comparison with other fuels. These problems have been overcome by adding hydrogen to the air mixture at a point where and when the conditions for pre-ignition are less likely. This can be made by delivering the fuel and air separately to the combustion chamber and/or injecting hydrogen under pressure into the combustion chamber before the piston is at the top dead centre and after the intake air valve has been closed [4]. Other techniques are water injection and exhaust gas recirculation that will help to control the premature ignition.

Hydrogen fueled internal combustion engines can be used for both power generation and transportation. Most of the investigated literatures are about hydrogen fueled engines for transportation in cars and busses. The problems and experiences from these engines should be valid for engines for electricity production as well.

It has been demonstrated that a wide range of engines can be converted to run on hydrogen. In general the performance has been enhanced [6]. An ICE, originally designed for gasoline, can use hydrogen as fuel. Used in ICE, hydrogen has the highest efficiencies, lowest operating temperatures (at a low fuel to air ratio) and lowest emissions of any fuel. A reason for this is the low fuel to air ratio, which can be used in hydrogen engines [7].

The thermal efficiencies for various single-cylinder research engines are plotted in Figure 3.1 below. Also, the ideal thermal efficiency and the ideal thermal efficiency reduced with 12% (to account for engine friction) are plotted in Figure 3.1. From Figure 3.1 you can see that the thermal efficiency can reach 45-50% at high compression ratios.

![Figure 3.1, Thermal efficiencies of various research engines [8]](image-url)
3.3 Research and Development

Most of the research on hydrogen ICE has been conducted with modifications of existing engines designed for gasoline. A new design of the combustion chamber and coolant systems that accommodate the unique combustion properties of hydrogen could be the most effective method to solve the problems of preignition and knocking.

Two key areas under examination are the fuel delivery system and the ignition system. In a carburetion system, premixing creates a lean homogenous mixture that keeps NOx-emissions low. Preignition and flashback are better prevented in a fuel-injected system [5].

Another focus on research is reducing the NOx-emissions in fuel injection systems by diluting the intake air mixture in a direct-injection ICE [5]. This can be realized by recirculating exhaust gases or by scavenging. These techniques result in reduced flame temperature and reduced oxygen availability of the hydrogen/oxidizer mixture. DOE, U.S. Department of Energy, are involved in a hydrogen program. One aim of this program is to try to demonstrate an integrated ICE/delivery/storage system with efficiencies approaching 45% (in transportation) [9]. In the WE-NET program a zero-emission closed cycle diesel engine cogeneration system of 600-1000 kW were studied. The expected electrical efficiency is 45-50% (LHV). The development of main components such as hydrogen injector and igniter has been started [1].

3.4 Demonstration plants/engines

3.4.1 Sandia National Laboratory

In a collaboration with Los Almos and Lawrence Livermore National Laboratories, Sandia National Laboratory is developing a hydrogen fueled engine for a generator set or hybrid vehicle application. The goal is to achieve a high thermal efficiency while satisfying low emissions without any exhaust gas after treatment. The design approach for this is to utilize hydrogen’s unique characteristics of high flame speed and ability to spark ignite homogenous mixtures at low equivalence ratios. The used engine is a modified Onan 0.491 liters single cylinder Diesel engine with a compression ratio of 14. The highest recorded indicated thermal efficiency was 44% (peak value) [10].

3.4.2 Hydrogen ICE powered automobiles

In the mid-1920s a German engineer Rudolf Erren began to convert engines to run on hydrogen for a variety of applications including trucks, buses and submarines. Since 1970 a significant amount of research work have been done in this area. This work has been mainly aimed to convert existing IC engines to run on hydrogen and studying the problem of hydrogen storage in vehicles [4].
3.4.3 BMW

BMW in Germany are developing combustion engines for hydrogen. BMW has selected to use hydrogen as a choice together with conventional fuels. Figure 3.2 shows an engine, which can use both hydrogen and gasoline. This is needed during the building of the hydrogen infrastructure.

Figure 3.2, A hydrogen/petrol engine from BMW

Several BMW vehicles have since 1979 been retrofitted and modified to use hydrogen, see Figure 3.3. BMW has made significant improvements on engines, such as the first direct injection of hydrogen into the cylinder [4].

Figure 3.3, Hydrogen powered BMW automobile [4]
3.4.4 **Daimler-Benz**

Since 1973 Daimler-Benz has been studying the possibilities to use hydrogen as a fuel for vehicles. The early work culminated in a fleet test of hydrogen vehicles, which began 1984. Five vehicles (model 310 delivery van) were converted to run on pure hydrogen. During the four-year test period the vehicles operated reliably and safely [4].

3.4.5 **Mazda**

In 1991 Mazda introduced their first hydrogen fueled concept car, the HR-X. The car had a compact rotary engine, see Figure 3.4. The rotary engine is, in some ways, ideal for use with hydrogen since the operational chamber moves so that the intake, compression, combustion, and exhaust strokes occur at different places. In this way, backfire and preignition, can be reduced since the temperature during the intake stroke is low and there is no direct contact between the air/fuel mixture and the exhaust gases. Lower combustion temperatures can also lead to a reduction in the exhaust emission levels [12].

![Figure 3.4, A hydrogen rotary engine from Mazda][11]

Later on Mazda has released an updated version of the HR-X, the HR-X2, a Miata and a 626 station wagon, all equipped with rotary engines [4, 12]. The HR-X2 is shown in Figure 3.5, Mazda's hydrogen-fueled HR-X2. The HR-X2 engine achieves a maximum power of 130 hp (97 kW) and a maximum torque of 17 kg/m. The rotary engine used in the Miata generates 118 hp (88 kW).
Figure 3.5, Mazda's hydrogen-fueled HR-X2

3.4.6 MAN liquid hydrogen City bus

MAN Nutzfahrzeuge Aktiengesellschaft has developed a bus power by hydrogen, see Figure 3.6. The bus is driven by an internal combustion 4-stroke Otto engine (MAN E 2866 DUH [13]) that can operate both on hydrogen and gasoline. The air/fuel ratio is just under lambda = 1. The bus was demonstrated between 1996 and 1998 on scheduled service runs in the cities of Erlangen and Munich.

In gasoline mode the engine attains a maximum output of 170 kW at 2200 rpm. The corresponding output is 140 kW in hydrogen mode [14].

Figure 3.6, MAN City bus SL 202
4 Gas Turbines

4.1 Background
There are many reasons why hydrogen is a good substitute for fossil fuels as gas-turbine fuel. The combustion products contain no CO₂, SOₓ, CO, HC etc. There are no fuel NOₓ, just thermal NOₓ formed due to the intake air [22]. This leads to no or easier after-treatment of the exhaust gases. A hydrogen-operated gas turbine installation does not produce any ash particles and other residue. The problems with corrosion and deposits on blades are thereby avoided. The combustion dimensions can be made smaller sized because of the high combustion speed of hydrogen compared to conventional fuels. Hydrogen is the best fuel from the viewpoint of thermodynamics due to its high combustion temperature. Hydrogen fueled gas turbines will operate with higher temperatures. This will increase the thermal efficiency but can also increase the NOₓ-emissions. The exhaust from hydrogen turbines are not chemically aggressive which makes it possible to use less-expensive materials for air preheaters etc. fed by the exhaust gases.

4.2 Current status
There are today only in experimental operation a few gas turbines running on pure hydrogen. More common tests are gas turbines running on mixtures of hydrogen and natural gas.

4.3 Research and Development

4.3.1 WE-NET - Development of a hydrogen combustion turbine
The WE-NET project is divided in three phases extending from 1993 to 2020. NEDO is researching and developing hydrogen energy technologies in a joint industry-government-university effort.

A hydrogen combustion turbine will be an extremely clean system for the environment. No carbon dioxide, sulfur oxide and nitrogen oxide at all will be emitted due to the combustion turbine only use hydrogen and oxygen. The electric efficiency of a hydrogen combustion turbine is expected to be over 60% (HHV) or 70,9% (LHV) [15] for a 500 MW combined cycle power plant. In phase I NEDO will investigate the system optimization, the combustion control technology, major components (turbine blade, rotor etc.), major auxiliaries and super-high temperature materials. These research results will eventually be applied to a hydrogen combustion turbine at a pilot plant [16]. A hydrogen combustion turbine cycle used for industrial power plant with high capacity has never been realized in the world. A 50 MW prototype plant is planned to be produced and operated by 2020 [17] with a thermal efficiency greater than 64,9% (LHV) [15]. A conceptual model of a hydrogen combustion turbine is shown in Figure 4.1.
Phase 1 is divided in nine subtasks. Subtask 8 named "Development of a hydrogen combustion turbine" is divided in the 5 subgroups described below [18]. Subgroup 3 and 4 have been managing by Japan Power Engineering and Inspection Corporation (JAPEIC) and the others by Central Research Institute of Power Industries (CRIEPI) [19]. The goals of subtask 8 include a thermal efficiency greater than 70.9% (LHV) or 60% (HHV) for a hydrogen gas turbine combined cycle, a Reliability-Availability-Maintainability equivalent to current base-loaded natural gas-fired combined cycles, and elimination of CO$_2$, NO$_x$ and SO$_x$ during power generation.

1. Study of an optimum system for hydrogen combustion turbine

To achieve a high thermal efficiency they have considered applying a combined cycle of a gas turbine and steam turbine or a new Rankine cycle. The turbine inlet temperature (TIT) will be 1700°C. The efficiencies of the other process components must be high, such as 89% of adiabatic efficiency of compressor and 93% for the turbine [18]. Three companies in Japan and USA, Mitsubishi Heavy Industries, Toshiba and Westinghouse, proposed three conceptual systems, "Topping regenerative cycle", "New Rankine cycle" and "Reheat regenerative Rankine cycle". The optimum cycle was after careful evaluation by experts and university professors found to be the "Topping regenerative cycle", see Figure 4.2. This cycle is most advantageous from the point of view of the thermal efficiency and feasibility of components. This task was completed in 1996.
Figure 4.2, Closed Circuit Cooled Topping Recuperation Cycle 500 MW [17]

The cycle in Figure 4.2 consists of a closed Brayton cycle as top cycle and a Rankine cycle as a bottoming cycle. The topping cycle are composed by a low-pressure compressor (CP1), a high-pressure compressor (CP2), a high temperature turbine (4), a combustor (3) and the heat exchangers 5, 6, 14 and 15. The heat exchangers 14 and 15 improve the thermal efficiency by recuperating heat from the turbine exhaust to the inlet of the combustor. The cycle has a closed circuit cooling system, which improve the thermal efficiency by reducing the losses from the cooling media.

The first stage vane height of the high temperature turbine (4 in Figure 4.2) will be around 85 mm for the chosen cycle [17]. This makes it easier to construct the complicated cooling passages inside the vanes and blades compared with the other cycle alternatives, which will have shorter vanes. It is also easier to reach higher aerodynamic efficiency of the turbine.

2. Development of combustion control technology

A key technology to realize is the combustion of hydrogen and oxygen in inert gas such as steam. For these purposes and to clarify combustion characteristics combustion tests have been carried out by some types of small model combustor, such as annular and can type.

The tests show that complete combustion of hydrogen and oxygen is difficult, and either hydrogen or oxygen remains when they are burnt at an equivalence ratio [3].
Desirable results from these tests are basic data regarding possible reduction of residual hydrogen and oxygen near the stoichiometric ratio, proper cooling and dilution structures of combustor wall and measuring methods of temperature and concentrations of residual hydrogen and oxygen in the exhaust gases from the combustor.

3. Development of turbine blades, rotor and other major components
One of the most important technologies in a high temperature turbine is the cooling technology. The cooling of the rotor disk and the sealing technology is also quite important to achieve a high thermal efficiency.

The project conduct tests for several types of blade cooling, for example, film cooling, hybrid cooling (film + steam convection), steam convection cooling and steam cooling/Water cooling. 1997 and 1998 Mitsubishi Heavy Industries (MHI), Hitachi Ltd. and Toshiba Corporation designed and fabricated three different models of turbine blades. These blades will be tested at Tashiro Hydrogen Combustion Test Plant. These tests were scheduled to end in late December 1998 [19].

The combination of a closed-circuit water cooling system for the nozzle blades and a steam cooling system for the rotor blades was found to be the most efficient. A conceptual design of the cooling circuits and gas path for this system is shown in Figure 4.3.

Figure 4.3, Schematic view of gas path and cooling circuits of gas turbine [20]

4. Development of major auxiliary equipment
WE-NET have studied two types of hydrogen-oxygen supply system. The evaporation of the liquid hydrogen can be used to produce oxygen.

Also, conceptual design of high temperature heat exchangers and a study of its compactness and safety are performed. One of the core developments in the WE-Net projects is the development of very hot side heat exchangers. Examples of the temperature and pressure conditions for the heat exchangers are 716°C/50 bar and 593°C/350 bar [21]. Pressure differences up to 350 bar can be reached between both sides in a heat exchanger. This together with the high temperatures makes it difficult to construct suitable heat exchangers.
5. Development of super heat-resisting materials

It is necessary to develop materials that are usable under super high temperature circumstances. Another important thing among others is to study machining technology.

### 4.3.2 Westinghouse

Westinghouse has worked to develop a hydrogen-fueled combustion turbine system (working with oxygen) designed to meet the goals set by the WE-NET Program describes above. These goals include a thermal efficiency greater than 70.9% (LHV) or 60% (HHV), a Reliability-Availability-Maintainability equivalent to current base-loaded natural gas-fired combined cycles, and elimination of CO₂, NOₓ and SOₓ during power generation. Westinghouse proposed a long-term Rankine cycle with reheat and recuperation with a net thermal efficiency of 71.4% (LHV) [15], see Figure 4.4, Westinghouse Near-Term plant cycle with a thermal efficiency of 65.2% (LHV) is shown in Figure 4.5.

![Figure 4.4, Long-Term Plant Cycle (Westinghouse)](image1)

![Figure 4.5, Near-Term Plant Cycle (Westinghouse)](image2)
4.4 Problems

There remain problems to solve before a hydrogen gas turbine system can be on the market. Some of them are described below.

- The high temperature, especially when hydrogen fueled gas turbines operate on pure oxygen, require temperature resistant materials. Also, better cooling technique is required.
- Hydrogen’s high flame speed requires a change in the design of the burner.

4.5 Demonstration plants/turbines

In Japan, a small-scale hydrogen gas turbine originated from a commercially produced lightweight car turbo-charger has been selected as a practical candidate in constructing an alternative hydrogen energy system. Its characteristics have experimentally been examined [22]. The experimental layout of a hydrogen gas turbine is shown in Figure 4.6. The turbine and the compressor are both axial radial flow types and connected to one shaft. The turbine has 12 ceramic blades of 52 mm in diameter and the compressor has 10 metal blades of 52 mm in diameter.

![Figure 4.6, Experimental layout of hydrogen gas-turbine [22]](image)

At a turbine speed of 30 000 rpm the power output is 16 kW. Typical experimental results are shown in Figure 4.7 where the turbine output Lt (kW) and theoretical thermal efficiency are shown at different turbine speed (rpm). A maximum efficiency of 34 % is reached at N ~35 000 rpm where the output Lt is ~18 kW.

Alternative small-sized hydrogen energy system schemes including gas turbines like the above described one with the order of 10 kW output are suitable for house- and office-use to decentralize power generation and to recover waste energy.
Figure 4.7, Hydrogen gas turbine performance [22]
5 Steam generator

The result from combustion of hydrogen and pure oxygen is pure steam.

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

The combustion of hydrogen and oxygen would develop temperatures in the flame zone above 3000°C. Therefore, additional water is injected to lower the temperature to below 1500°C. Saturated and superheated steam can both be produced. The steam generator can produce steam that can be used in a steam turbine power plant.

The German Aerospace Research Establishment (DLR) has developed a compact hydrogen/oxygen steam generator, see Figure 5.1. The steam generator consists of the ignition, combustion and evaporation chamber. A combustible mixture of hydrogen and oxygen at a low oxidant/fuel ratio is ignited by a spark plug in the ignition chamber. In the combustion chamber the rest of the oxygen is added so the stoichiometric ratio is reached. Water is also injected in the combustion chamber to control the temperature. The steam is homogenized in the evaporation chamber. The generator has almost 100 per cent efficiency, since there are no emissions and little or no thermal losses. The steam generator is rated 40 MW [4].

Figure 5.1, H₂/O₂ steam generator [4]
6 Gas Boilers

Hydrogen can be burnt in gas-fired heating boilers. A boiler designed for natural gas can be converted to hydrogen by modifying the burner. When burning hydrogen more water vapor is produced. If all or parts of the water vapor present in the flue gas can condense, the energy conversion can increase by as much as 18 % when referring to the lower heating value (LHV) [23]. Another aspect is that burning hydrogen can cause a higher combustion temperature. High temperatures encourage the formation of nitrogen oxides (NOₓ). Increasing the excess of air (resulting in a lower burning temperature) can reduce this formation.

In a demonstration project at a site in Neunburg Vorm Wald under phase 1 in the Solar Hydrogen project in Germany two gas-fired heating boiler units with modified burners were installed, see Figure 6.1. They were capable of burning hydrogen, natural gas or mixtures of both gases. One purpose of the project was to investigate the possible transition from fossil origin fuels for conventional gas-fired heating boilers to the possible supply of hydrogen.

The boilers had a capacity of 20 kW each with a flow/return water temperature range of 40/30 to 70/50°C. The boilers were standard models with top combustion chamber. The left boiler in Figure 6.1 operated with oxygen as oxidizer and the right boiler with air as oxidizer. There were only some small problems during an operation period of one year. Efficiencies from the test at 20 kW capacity and water temperature 40/30°C are showed in Table 6.1 below.

Table 6.1, Efficiencies at nominal capacity and water temp. 40/30°C

<table>
<thead>
<tr>
<th>Fuel gas</th>
<th>Efficiency (%) with air</th>
<th>Efficiency (%) with oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>103,5 (LHV)</td>
<td>112,8 (LHV)</td>
</tr>
<tr>
<td>Natural gas</td>
<td>97,4 (LHV)</td>
<td>105 (LHV)</td>
</tr>
</tbody>
</table>
Catalytic Burners

In the presence of a suitable catalyst hydrogen and oxygen may be combined at temperatures significantly lower than flame temperatures (from ambient to 500°C). Catalytic burners are designed after this principle. Catalytic burners require considerably more specific surface area than conventional flame burners. The catalyst is therefore dispersed in a porous structure. By controlling the hydrogen flow rate the reaction rate and resulting temperature can easily be controlled. The reactions take place in a reaction zone of the porous catalytic sintered metal cylinders or plates. In this zone, hydrogen and oxygen are mixed by diffusion from opposite sides. A combustible mixture of hydrogen and oxygen is only formed in the reaction zone. Assisted by a catalyst (platinum) the mixture burns at low temperatures giving only water vapor as product (Figure 7.1). Due to the low temperature no nitrogen oxides are formed [4]. Also, the reaction can not migrate into the hydrogen supply since there is no flame and hydrogen concentration is above the higher flammable limit (75 per cent).
Figure 7.1, Schematic representation of catalytic burner [4]

Hydrogen is more dangerous to use in a catalytic burner than natural gas due to hydrogen's high reactivity and high flame speed [24]. Therefore, the fuel inlet needs to be designed for hydrogen use. At higher pressure the energy content in the gas increase, which increase the consequences of an explosion.

Katator AB in Lund in Sweden is developing catalytic burners. They have with good results performed tests with a 10 kW hydrogen fueled catalytic burner [25]. The catalytic burner was aimed for a German car manufacturer working with fuel cells.
8 Hydrogen powered airplanes

The use of hydrogen in turbines and jet engines is similar to the use of conventional jet fuel. Hydrogen use will avoid the problems of sediment and corrosion on turbine blades due to hydrogen’s lack of impurities and its cleanliness. This prolongs life and reduces maintenance. The gas inlet temperatures can be raised beyond the normal temperatures of 800°C and thereby increasing the overall efficiency. Another advantage is the low combustion products, water vapor and only small amounts of nitrogen oxides.

Liquid hydrogen as a fuel has several advantages for commercial subsonic and especially supersonic aircraft. The most important advantage is its high energy content (per mass, 2.8 times higher than for conventional jet fuel) [4]. A liquid hydrogen powered aircraft would therefore have to carry one third of the fuel mass of a conventional aircraft. This means smaller engines, higher fuel utilization, reduced noise and more payloads. A subsonic hydrogen fueled passenger aircraft will on average need 16 per cent less fuel than a comparable conventional aircraft to complete the same flight. This advantage is higher in a supersonic aircraft (28 per cent).

Due to the low density of the fuel a hydrogen-fueled aircraft will generally have a slightly lower lift-to-drag ratio (L/D) and a lower wing loading than conventional aircraft. Hydrogen requires a very large volume. This is the reason why the L/D-ratio is lower despite the fact that liquid hydrogen only requires one third of the mass. It has been found advantageous to carry the fuel (LH$_2$) in the fuselage resulting in larger fuselages than for conventional aircraft. Because of the low weight of fuel, the LH$_2$ aircraft is much lighter to take-off and therefore needs less wing area. Liquid hydrogen can also be used as heat sink so that hot parts of the engine can be cooled effectively and efficient.

Another aspect is that hydrogen is actually a safer fuel for air transportation than presently used jet fuel. This is because of hydrogen’s characteristics and a different construction of hydrogen fueled aircraft [4].

A commercial airliner (Tupolev 154) with one of the three turbofan engines fueled with liquid hydrogen was demonstrated in April 1988, see Figure 8.1. In June 1988 an American pilot became the first to fly an aircraft fueled only by liquid hydrogen [4].
German and Russian companies, including Daimler-Benz Aerospace, and its divisions Airbus and Dornier, and Tupolev, have since 1990 been jointly working on the development of hydrogen-powered propulsion technology for civilian aircraft, see Figure 8.2. Project activities are currently been concentrated on the following topics:

- Development of technologies and components for the cryogenic fuel system and the engines of future series aircraft
- Realization of a hydrogen demonstrator aircraft

A Dornier 328 aircraft equipped with two Pratt & Whitney Canada PW 119 engines has been selected as a baseline for a hydrogen demonstrator. The first flight is estimated for late 1999 [4].

Figure 8.1, Tupolev 154 - first commercial aircraft flying on hydrogen fuel [4]

Figure 8.2, Liquid hydrogen powered concept airplane (Airbus) [4]
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