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A PROPOSAL OF A HYDROGEN INJECTION SYSTEM IN TO A MINIATURE TURBOJET ENGINE

Propozycja układu wtrysku wodoru w miniaturowym silniku turboodrzutowym

Abstract: *The solution proposed in this article, based on direct injection of hydrogen into the combustion chamber, offers many benefits, including a better volumetric efficiency, complete combustion (avoidance of premature ignition and backfire) and significant benefits in terms of power density when compared to engines, in which hydrogen is injected into the air inlet duct. The article discusses advantages and disadvantages of systems responsible for injecting hydrogen into the combustion chamber based on the operational phases of the GTM 400 engine developed by the JET-POL Company. The use of an electronic controller combined with an injector placed in an appropriate place inside the combustion chamber allow for the mentioned engine to be modified this way to optimize its power, performance and emissions. The article discusses matters related to challenges faced by materials used to make components of hydrogen injectors as well as research on the topic in question with the use of diesel engines. The article considers the impact of a low mass density and hydrogen energy, high speed of sound and low thickness on the injection system and components of a miniature turbojet engine. Physical attributes shaped by hydrogen fuel directly affect the size of components, selection of materials and tribology of turbojet engines. The authors suggest that the solutions used in the research on the GTM 400 engine can be used in the future to build hydrogen systems (hydrogen injection, storage and distribution) for fullscale passenger aircraft jet engines.*
Keywords: hydrogen, miniature turbojet engine, hydrogen injection system

Streszczenie: *Opracowanie odpowiednich systemów wtryskowych do miniaturowych silników odrzutowych dedykowanych do paliwa wodorowego może zaowocować opracowaniem urządzeń wykorzystywanych w układach generacji energii elektrycznej w infrastrukturze krytycznej. Zaproponowane w artykule rozwiązanie bazujące na*

bezpośrednim wtrysku wodoru do komory spalania zapewnia wiele korzyści, w tym lepszą sprawność objętościową, pełne spalanie (unikanie przedwczesnego zapłonu i wstecznego zapłonu) oraz znaczne korzyści w zakresie gęstości mocy w porównaniu z silnikami z wtryskiem wodoru do kanału powietrza dolotowego. W artykule omówiono wady i zalety systemów dostarczania wodoru do komory spalania w zależności od faz pracy miniaturowego silnika GTM 400 firmy JET-POL. Zastosowanie elektronicznego sterownika w powiązaniu z wtryskiwaczem ulokowanym w odpowiedniej lokalizacji komory spalania pozwala na taką modyfikację wspomnianego silnika, aby zoptymalizować jego moc, wydajność i emisyjność. W artykule poruszono zagadnienia związane z wyzwaniami dla materiałów stosowanych na podzespoły do budowy wtryskiwaczy wodoru, a także prowadzone w tym zakresie badania na bazie silników diesla. Podjęta w treści dyskusja dotyczy wpływu niskiej gęstości masy i energii wodoru, wysokiej prędkości dźwięku i niskiej lepkości na system wtrysku i podzespoły miniaturowego silnika odrzutowego. Atrybuty fizyczne determinowane przez paliwo wodorowe bezpośrednio wpływają na rozmiar komponentów, dobór materiałów i trybologię silników odrzutowych. Autorzy sugerują, że rozwiązania zastosowane w toku badań nad silnikiem GTM 400 mogą posłużyć w przyszłości do budowy systemów wodorowych (systemy wtrysku, magazynowania i dystrybucji wodoru) dedykowanych pełnowymiarowym silnikom samolotów pasażerskich.
Słowa kluczowe: wodór, miniaturowy silnik odrzutowy, system wtrysku wodoru

1. Introduction

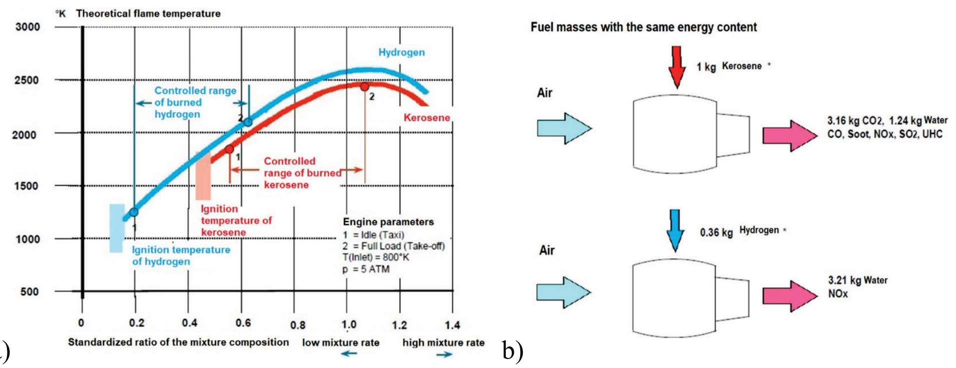
Both the energy and the transportation sector consider hydrogen-powered turbojet engines (direct injection) to be a highly efficient and low-emission bridge technology used as a smooth transition to hydrogen economy. The solution proposed in the article, based on fuelling a hybrid turbojet engine with hydrogen and jet kerosene, allows the existing airplane propulsion systems to remain while introducing only the additional much lighter and smaller hydrogen tanks with their accessories. A solution of this type is competitive to the currently used fuel cells. The use of the existing technologies developed specially for jet kerosene-powered jet engines makes this solution extremely attractive from the economical point of view. The article at hand does not take up matters as essential as on-board hydrogen storage and distribution systems and focuses only on the technology, which can be successfully implemented to develop the injection systems.

Still, the issue of creating hydrogen in an economical way, that is, without high emission of greenhouse gases, remains unsolved, but achievable in the long term. Although those are very important matters, they are not discussed in this article. Nevertheless, they constitute factors necessary to achieve success in the transformation of critical infrastructure towards “the blue fuel.”

Gas turbines, which use hydrogen in the gaseous form as fuel injected into the combustion chamber with the use of modified injectors, demonstrate lower burning proportions of the mixture than kerosene (Fig. 1a). A less saturated mixture burning at lower temperatures leads to a cleaner burning process reflected in a low content of harmful substances (Fig. 1b). The result of the above-mentioned process is a cleaner gas turbine without soot, CO_2 and CO emissions and with five times lower NO_x emission. Unfortunately, an issue when fuelling turbojet engines with hydrogen is a higher content of water vapour. Currently, the influence of the increased amount of water vapour on the operation of hydrogen-powered turbojet engines is being researched [7]. Ice crystals, created within condensation smudges during the flight will become larger and thinner. It will be necessary to execute flight tests in order to precisely assess the scale of the problem and learn about the way in which unfavourable impact of condensation smudges on hydrogen-powered turbojet engines can be avoided or alleviated with the implementation of constructional changes in propulsion systems [3].

A problematic technology in terms of a hydrogen-powered passenger aircraft with a gas turbine is not the engine, but tanks and the fuel system.

An insurmountable obstacle for modern constructors of gas engines is to develop an H_2-powered turbine of a new class of power. To do that, it’s crucial to use electronic hydrogen injection systems. Research carried out at the Institute of Thermal Energy of the Poznan Technical University (IEC PP) attempted to power a miniature JET-POL turbojet engine with hydrogen (for the time being as a simulation in the Fluent environment; the installation with an injection system is being developed). The suitable power range is to be achieved by correct control of the injection system, which main part consists of piezoelectric injectors.



a) b)

Fig. 1. Analysis of the hydrogen burning process a) possible proportions of the mixture to burn hydrogen and jet kerosene b) kerosene and hydrogen-powered gas turbine emissions. Source: own work based on tests conducted by Airbus Cryoplane

The architecture of the hydrogen injector proposed in the research has to undergo additional tests. However, the presented solution is a serious step towards hybridization of miniature GTM turbojet engines developed by the JET-POL Company. The use of piezoelectric injectors (Fig. 2a and b) to distribute hydrogen imposes certain limitations related to the durability of those devices [11]. Based on the tested J43P_x injectors of the Westport Company, fixed inside the combustion chamber of a one-cylinder diesel engine, it is possible to conclude that in comparison to liquid hydrocarbon fuels, hydrogen is a difficult liquid to be used in precision injectors. The reason for that is a very low viscosity of hydrogen, its low density and the ability to alter the properties of the material by atomic diffusion or chemical reduction. IEC PP's specialists, together with author of this article as the originator of the project, intend to subject the developed hydrogen injection system to long-term effects of this fuel on a specially developed test bed with the GTM 400 engine. In the future, by solving the problem of erosion affecting the construction of the hydrogen system, it will be possible to develop both materials and a model of the injection system to be adapted in a fullscale aircraft engines.

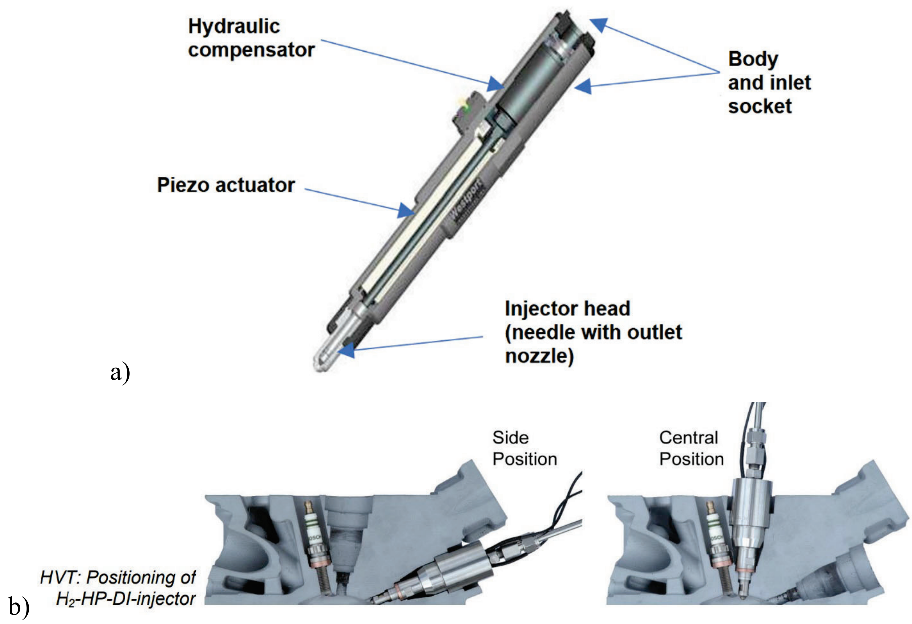


Fig. 2. Hydrogen injection devices for the combustion chambers of the combustion engines: a) internal structure of the J43Px Injector made by Westport company [11], b) the concept of installation in the combustion chamber of analogous H2BVplus HOERBIGER injector made by BMW [4]

Similarly, to conventional diesel engines, in the case of using piezoelectric injectors in turbojet engines, the following conditions of the injector head operation have to be taken into consideration:

- minimum temperature of the engine block from -40°C to 125°C;
- working temperature of the head from -40°C to 300°C;
- pressure for the distributed fuel 50-250 bar.

As a consequence, when the GTM engine is powered with hydrogen, the injector system is exposed to serious erosion while working, both as a result of dry hydrogen impact and high temperature. Therefore, a cooling system will have to be created together with a system to lubricate the parts of internal injectors. Distribution of temperatures in working conditions inside the combustion chamber of the GTM 400 engine, as well as the injectors, will be measured with the use of specially designed system of thermal vapours located inside the test channels. Temperature tests will be carried out first while working with the use of jet kerosene and then with hydrogen. By mapping parameters of the GTM 400 engine in working conditions with thermal vapours as well as a thermal vision camera, a temperature distribution map will be developed to confirm the simulation tests.

Overview of modifications introduced to the injection system of the GTM 400 engine

In most cases, test engines with a direct hydrogen injection use a centrally fixed 4-valve injector, which is similar to the modern ignition-compression engine. Direct Injection (DI) can eliminate the tendency of the engine to backfire inside the inlet collector and minimize premature ignition, because the time spent by fuel in the manifold can be shorter (based on the injection timing strategy). In the case of DI there is no flammable mixture in the inlet manifold.

Replacement of injectors in places indicated in Fig. 3 is not accidental. In the expected places within the combustion chamber, in the area of the ending of the hydrogen distribution duct, fuel fumes mix with air delivered from the compressor. The proposed direct injection DI can eliminate the tendency of the engine to back-fire towards the evaporators. It minimizes the tendency for premature ignition because the time spent by fuel in the given area can be shorter.

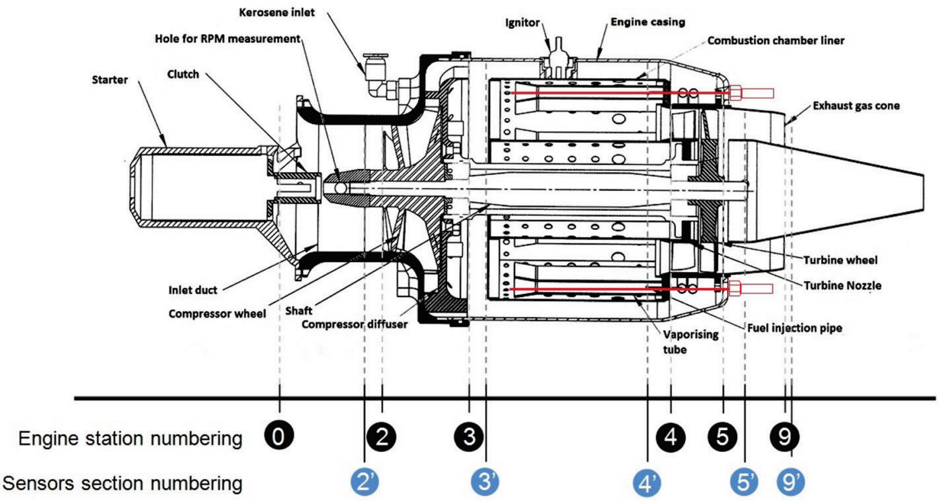


Fig. 3. Illustrative scheme of GTM 400 engine with injector fixing points (source, own work on the basis of: A. Welch, D. Mumford, S. Munshi et al., Challenges in Developing Hydrogen Direct Injection Technology for Internal Combustion Engines, Westport Innovations Inc. [1])

However, everything depends on the strategy adapted to control the jet kerosene injection in combination with H_2. Developing a proportional composition of a mixture consisting of two types of fuel requires laboratory tests supervised by microcontroller software to control the ignition and mixture composition automation.

DI can significantly increase the capabilities of maximizing the engine power density (tests carried out for diesel engines [10, 12]) in comparison to injectors located laterally to the combustion chamber. Tests indicate that the placement of the injector in relation to the delivered fuel is of great significance, that's why in the simulation tests, the shape of the ending of the hydrogen distribution duct has to be designed correctly and optimized for hydrogen distribution. In engines with injectors placed that way, based on the conducted tests [11] and with the applied stoichiometric ratio of air-fuel mixture, it is possible for the power loss to occur even down to 18% in relation to the jet kerosene power supply. Air pushed outwards by hydrogen in the combustion chamber is the cause of that. In practice, such an amount of hydrogen is difficult to achieve without backfire (a highly unwelcomed occurrence), when the compressor distributes pressurized air, especially at higher loads. As a result, the nominal power of a hydrogen and jet kerosene-powered engine can further decrease, because it can achieve only 65% of its torque, the same as a conventional engine of similar size [4]. And vice versa, hydrogen-powered engines with direct injection can exceed the power limit of a petrol engine. The correctly designed hydrogen distribution system can significantly increase the potential engine power and remove the power drop resulting from hydrogen being blown out [10, 12].

On the basis of the current research on powering conventional piston engines with hydrogen, it is possible to conclude that it is usually injected under pressure between 50 - 250 bars, depending on the engine combustion strategy. The data refers to piston engines, that's why establishing a time constant of H_2 injection and the value of its pressure when delivered to a turbojet engine require additional tests. It can be theorized that as in the case of diesel engines, the pressure ratio of 2:1 is required in the injection phase (injection pressure/pressure inside the combustion chamber). In the case of an earlier hydrogen injection, we receive a more homogenous air-fuel mixture (longer mixing time).

After preparing a fuel mixture, in a conventional miniature turbojet engine it is subsequently ignited with an ignition coil. Fuel can also be injected after ignition if the fuel pressure is much higher than the pressure inside the manifold. The hydrogen nuzzle ending introduced into the combustion chamber through the jet kerosene evaporator will be exposed to the highest temperature from its direct contact with the combustion area. The static distribution of temperatures upon ignition for a conventional mixture is presented in Fig. 4. Data comes from a simulation of powering the GTM-140 with jet kerosene [9]. The figure clearly shows that the temperature of the mixture at the evaporator outlet is within 460°C.

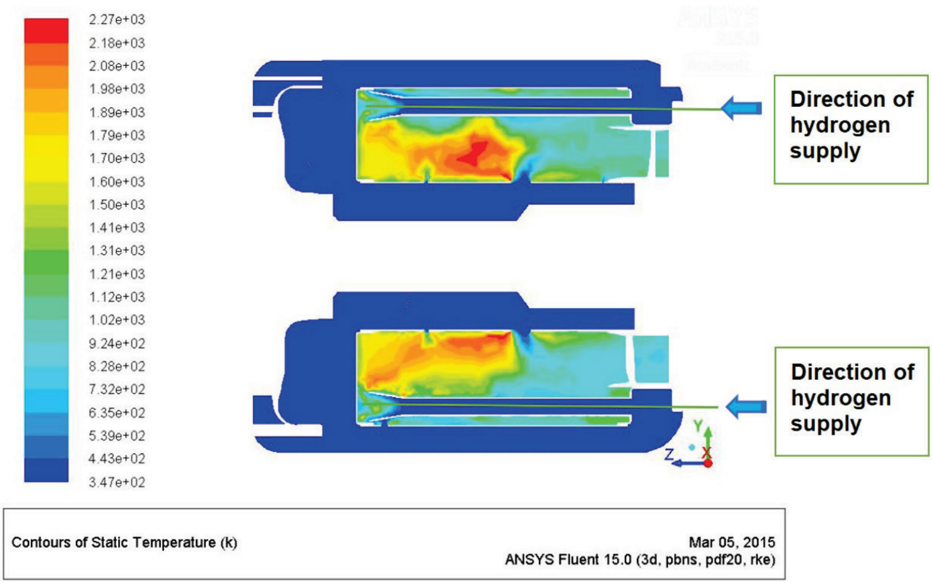


Fig. 4. Static distribution of burning temperatures for the air-fuel mixture in the GTM-140 engine – axial cross section (source, own work on the basis of [9])

In their work, L. Dodge and D. Naegeli [2] provide a number of dependencies describing the flow of hydrogen through the injector to the combustion chamber of a diesel engine. The tests were carried out for injectors located in a closed combustion chamber. On the other hand, tests of hydrogen accumulation in the tested chamber were carried out using a laser spectrometer (Fig. 5). Experimental measurements related to the mixing of hydrogen and air (L. Dodge and D. Naegeli used azote instead of air) for the DI system were carried out at Musashi IT [2]. Those experiments revolved around measurements of hydrogen fuel concentration and Rayleigh's light scattering of hydrogen and azote (background gas) in a high-pressure chamber by taking quick Schlieren photographs depicting the speed of hydrogen penetration into the chamber filled with azote. Measurements related to Rayleigh's light scattering allowed a relative molecular concentration of hydrogen and azote to be established.

The use of neutral gas a background for JETA1 and H_2 burning mixture in the GTM400 will enable a more detailed representation of the mixture distribution processes and its burning.

A JETMIX computer model was used to calculate hydrogen concentration below two. One millimeter diameter injector endings were used, with "straight" and expanded endings. Model results were compared to experimental results for hydrogen concentration measured with the Rayleigh's light scattering, and with penetration results measured with Schlieren photography. All results of the conducted experiments were developed by Musashi I.T [2].

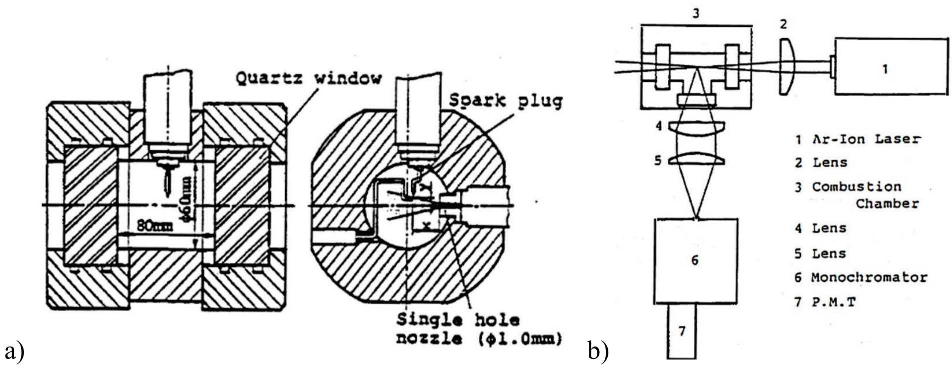


Fig. 5. Device developed by L. Dodge and D. Naegeli a) high-pressure chamber used for hydrogen injector tests b) optical system used for hydrogen concentration measurements (source: Musashi IT)

Comparison of the expected and measured hydrogen concentrations for the straight ending is shown in Figs. 6-9 for axial distances from the injector ending, 5, 10, 15 and 20 mm respectively. The pressure impulse came to 2,94 MPa, the pressure inside the chamber to 0,98 MPa, and the 17 mm long nuzzle orifice had a diameter of 1 mm.

Angle 22° of the stream cone was used for the calculations. Mass flow through the injector came to 0,896 · 10-3 kg/s (630 N L/min, 760 mm Hg, 15°C in normal conditions). The discharge ratio in the JETMIX model was adjusted to the value of 0,629 to correspond to the expected flow in relation to the measured value. It is a reasonable discharge ratio for a sharp-edged 17-milimeter opening with 1 mm in diameter. Numbers show that the cone angle measured for hydrogen was smaller than 22°. However, Schlieren photography shows that the cone angle was bigger. The differences between the described methods are not the subject of this article.

General conclusions of L. Dodge and D. Naegeli about the tests on the cone shape of the hydrogen injector nuzzle were positive, but absolute concentrations or hydrogen-azote ratios show some inconsistencies between the model and the experimental measurements (Fig. 6 a-d). Despite the bigger angle of the cone, the model assumes a higher concentration of hydrogen from the measured one. While maintaining the mass of the gas mixture assumptions should have been lower than the values measured at the middle line, if the shape would have been wider (bigger cone and angle). Molecular concentration rations are the same as volumetric rations of two gases, so those rations are comparable to the ones indicated in the model.

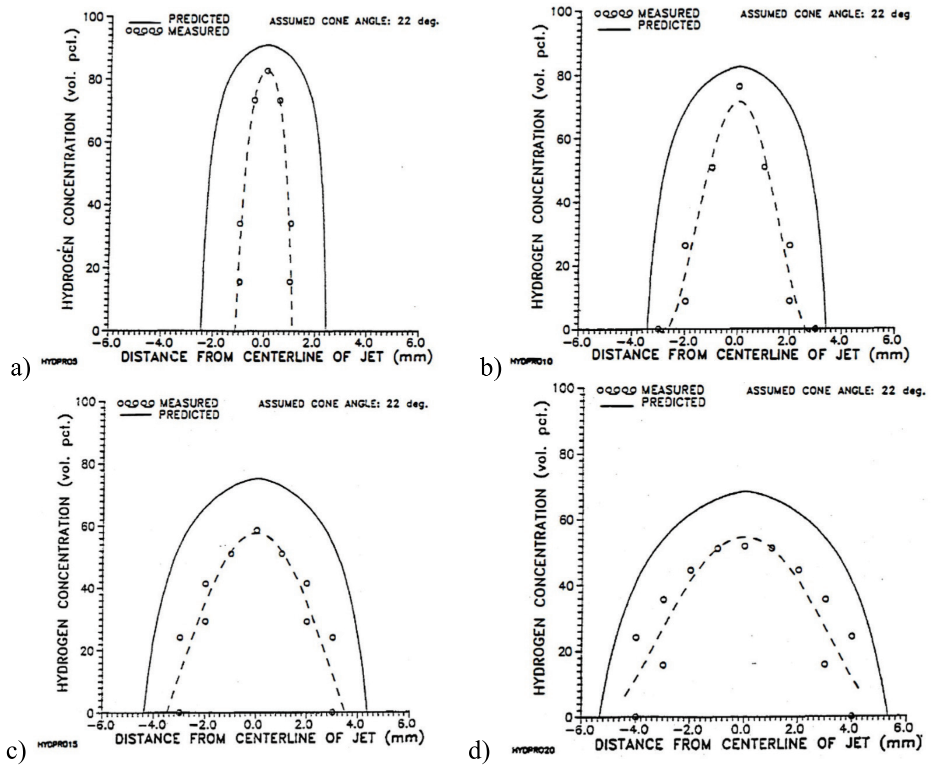


Fig. 6. Comparison of the expected (with the JETMIX algorithm) and calculated hydrogen fuel concentrations Azote-hydrogen stream for the straight ending of the injector (Pinj. = 2,94 MPA, Pchem. = 0,98 MPa); a) 5 mm; b) 10 mm; c) 15 mm; d) 20 mm.

The JETMIX model was developed for the injection of diesel fuel into a conventional diesel engine, where it is difficult to measure fuel concentration. Many technological differences between the injection of diesel fuel and hydrogen fuel while keeping the unique properties of the injected compressible gas, and not non-compressible fuel, are not considered in the JETMIX model. Therefore, it is an interesting research problem, which requires the development of an analogous model, both as simulations and tests, for a combustion chamber of a miniature turbojet engine. The JETMIX model was useful in predicting the behaviour of the H_2 stream inside the diesel engine. Although there were significant differences between the predicted and experimental profiles for concentration and penetration of the combustion chamber space by the hydrogen stream [2], subsequent experimental work and calculations allowed for establishing certain assumptions:

- mass concentration of the fuel flow through the nuzzle in each point of the axial cross section is the same and equal to the mass concentration of the fuel flow at the source;

- stream velocity in each point of the nuzzle cross section is the same and equal to the stream velocity at the source;
- it has to be assumed that the stream scattering angle is constant, and the velocity and fuel profiles, as well as the mass content, align with profiles described in Attachment A to the work of L. Dodge and D. Naegeli [2].

After the end of tests on the mixture of hydrogen and diesel in the previously mentioned combustion chamber (Fig. 4), work on the development of a hydrogen engine carried out at Ford Motor Company were oriented on testing the behaviour of hydrogen-diesel mixture inside a single cylinder of a specially developed piston engine (Ford Motor Company - single cylinder research engine [11]).

In the course of the tests, it was concluded that a wide range of hydrogen flammability ensures much freedom when it comes to choosing the injection strategy, depending on the working point of a piston engine. Figure 7 shows four basic strategies of injecting hydrogen based on the piston position: the bottom dead centre (BDC), intake valve closure (IVC) and upon mixture combustion - time direct combustion (TDC).

The tests were carried out both in low and high load conditions. A quick reaction of the injector and the multiplication of hydrogen injection for an additional control of mixture saturation allow efficiency to be optimized and affects NOx emission.

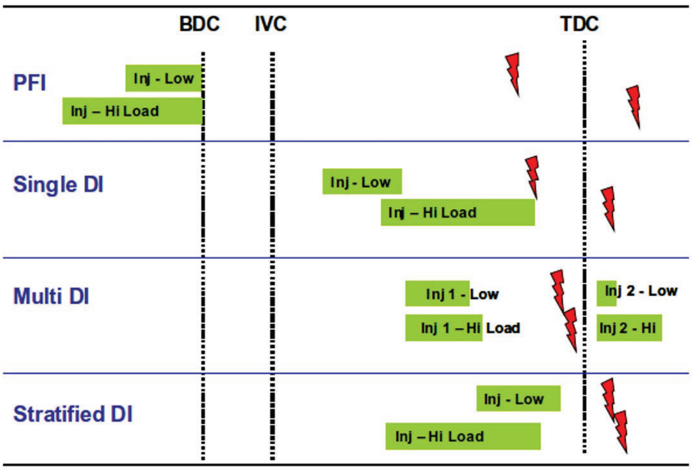


Fig. 7. Different strategies of hydrogen injection adapted for a single piston engine tested at Ford Motor Company [11]

Distribution of hydrogen in the case of a turbojet engine will require designing the fixing point of the injector inlet nuzzle and its shape to ensure direct hydrogen injection (similarly to a conventional diesel engine [11]).

The most appropriate moment for injecting hydrogen will depend on: the temperature inside the combustion chamber, air concentration degree and chamber space saturation with kerosene fumes from the evaporators. The conditions of injecting hydrogen into the combustion chamber cannot result in hydrogen retracting to the injector nuzzle and penetration of the flame towards the evaporator ending.

Designing hydrogen injectors is quite challenging when compared to injectors used for hydrocarbon liquid fuels and ground gas. Most of all, it is important to ensure long durability of the injectors and to achieve a high level of mass concentration of the working medium flow.

Table 1

Comparison of fuel properties: calorific value, sound velocity, density, dynamic viscosity, energy flow, flow regim [11]

Property	Units	Diesel (1-D)	Methane	Hydrogen
Lower Heating Value	[MJ/kg]	43	50	120
Speed of sound	[m/s]	1240	579	1625
Density	[kg/m^3]	727	144	15.1
Dynamic Viscosity	[cP]	0.836	0.020	0.011
Energy Flowrate (LHV) – 1 mm^2 hole	[MJ/s]	8.19	1.66	1.34
Flow Regime	[-]	Sub-sonic	Sonic	Sonic

Liquid fuels can deliver more energy per surface unit (MJ/s, lower calorific value) with simultaneous difference in pressures. It seems to be obvious due to their higher density (Table 1). Other factors have to be considered as well, for instance: is the liquid compressible or not, can combustion conditions be affected, is the flow subsonic or not. Based on Table 3, compared to hydrogen, the injector opening of 1 mm^2 diameter for diesel provides around six times more chemical energy (Energy Flow Rate (LHV)), with the same pressure differences (power supply of 25 MPa). It also has to be remembered that diesel flow is supersonic at a relatively low pressure (condition: pressure difference of 24.9 MPa) while both gases in the table (hydrogen and methane) quickly accelerate to reach the sound velocity at the narrowest section of the injector, usually under the needle/pit interface or at the nuzzle opening.

The M Mach number for hydrogen running through the nuzzle is calculated from the following equation:

$$\boldsymbol{M} = \left(\left(\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}} - \mathbf{1}\right)\frac{\mathbf{2}}{\gamma-\mathbf{1}}\right)^{\frac{1}{2}} \tag{1.1}$$

where p_0 is the pressure before the injector (pressure increase), p is the pressure inside the chamber, and γ – an isentropic exponent.

In modern injectors developed in common rail technology, diesel systems work in the regime of 200 MPa and higher. Hydrogen injection systems leave many problems to be solved, such as those related to the injector nuzzle dimensions, so that proper combustion condition can be maintained for low density of that fuel in engines organically adjusted to burn diesel or kerosene.

Challenges related to the development of piezoelectric hydrogen injectors can be divided into four areas:

- consumption related to the impact at the needle/pit junction;
- sliding consumption between the bottom needle and the area nuzzle/leading surface;
- hydrogen diffusion to the dielectric coating or piezoelectric actuator;
- integrity of tightness inside the hydraulic compensator.

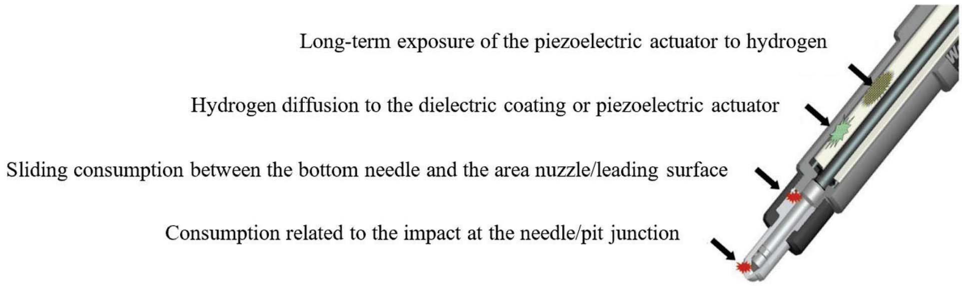


Fig. 8. Expected damage to hydrogen injectors [11]

A direct hydrogen injector of second generation had been developed during tests conducted at Ford facilities (fully electronic control of injection/direct effect), which provides the desired performance in many aspects: opening time, repeatability and peak intensity of flow during multiple injections. Subsequent tests of the engines showed their perfect performance [6]. Power density of mixtures created by piezoelectric injectors is evidently higher than in the case of conventional induction injectors. The tests of basic materials became necessary to identify mechanism responsible for hydrogen engine failures. It allowed Ford's scientists to direct their tests to develop injector components of proper shape with the use of new materials, which were durable to hydrogen erosion. The next task of scientists working on testing hydrogen-powered diesel engines leads to: significant extension of injector life from around 200 hours to 1000 hours. It would allow using hydrogen in early injection multi-cylinder engines together with advanced integrated fuel systems with direct injection. A long-term goal will be to develop and prove a 20 000 hour level of durability of the hydrogen/diesel propulsion system, with its construction intended for mass production, thanks to further tests of basic materials, tests on multi-injection platforms and full scale validation of the engine. The proposed research process by Ford will be implemented to develop a hydrogen/jet kerosene injection system for the GTM 400 engine.

When considering the same assumptions, the mentioned model of the physical properties of the nuzzle injector for diesel has to be modified for H_2 to provide proper fuel/air mixing speed.

The original equation related to mass concentration and diesel flow speed included in the work of L. Dodge and D. Naegeli [2] has been replaced with equations for compressible gases. Mathematical dependencies presented in the mentioned work can be implemented for combustion and hydrogen flow calculations for injectors to be used in the GTM engine.

In the future model of the injector nuzzle, it has to be accepted that the hydrogen will immediately expand at the injector outlet. Moreover, it is assumed that the velocity profile inside the injector is the piston flow with the same speed across the opening, while at the opening the stream has to move towards the profile calculated using the Gauss-Seidel method [6].

In order to solve the hydrogen expansion problem it can be assumed that the gas has already expanded inside the injector. This way, hydrogen density inside the injector is reduced from its factual density with the ratio between p_{bomb} to p_0, where p_{bomb} is the background pressure inside the chamber (Fig. 6), and p0 is the pressure before the injector. It is important to maintain the correct concentration of mass flow and hydrogen momentum inside the injector, so decreasing the gas density requires to increase the surface by the p_{bomb} / p_0 ratio. Mas flow of the fuel, velocity and total stream momentum are the same and constant in each section of the stream below the injector and inside it. It is also important to remember about the cone angle of the hydrogen stream from the injector, because according to L. Dodge and D. Naegeli [2] increasing it affects the speed of hydrogen mass flow through the injector and so for the cone stream angle of 22° it comes to 0.896 · 10-3 kg/s (630 N L/min, 760 mm Hg, 15°C in normal conditions). As for the angle of 33.4°, the mass flow reaches the value of 0.931 · 10-3 kg/s (655.0 N L/min) [11].

After the conducted tests related to the types of injectors, the shape of the hydrogen outlet nuzzle and hydrogen/diesel combustion, the next riddle to solve in conventional combustion engines is the matter of what can be used to develop a system to power a turbojet engine are electronic system to control the ignition and injection.

In piezoelectric injectors used to power a diesel engine with hydrogen [11], both hydraulic compensator and the needle (Fig. 2) are initially loaded with a springer. After voltage reaches the piezoelectric actuator, the nuzzle opens. Using such an actuator allows the opening of the nuzzle to be accurately controlled. Injector opening can be controlled with a controlled based on the PWN system. Control voltage is high and can reach values between 500 and 1000V. As the piezoelectric element of the actuator expands (to around 100 microns or 130 microns depending on the actuator model) it starts to put pressure on the hydraulic compensator which in turn raises the needle. In a very short injection period, usually 5 ms or less, the relative motion inside the hydraulic compensator is limited to the minimum. When the needle rises, hydrogen runs through the nuzzle, more or less as the needle rises. At the end of the injection period, the electrical charge is taken off the piezoelectric actuator, its length decreases and the whole system returns to the close position. It is possible to us a keyer system operated with an Arduino microcontroller to control the piezoelectric element. The use of a microcontroller allows developing a device to control the work of not only the injection system, but also the safety system by monitoring hydrogen flow and measuring operational parameters of the system powered by H_2. On the other hand it is possible to use existing controller like FADEC (Full Authority Engine Control) with specific upgrades for hydrogen operation.

2. Summary

Nowadays, replacing jet kerosene used to power aircraft propulsion systems with a purely electrical propulsion system does not guarantee that the existing aviation construction would have sufficient power supply. The implementation of such a solution would force the use of heavy batteries, and that would limit the number of passengers and the number of the transported cargo or weaponry. Therefore, it is only natural to look for solutions, which would be able to provide a sufficient power supply while decreasing the volume and mass of fuel tanks. Hydrogen turns out to be the most lucrative solutions, but currently costs of its creation remain high.

This chemical compound is common in nature and at proper pressure (with the use of cryogenic tank systems) will reduce the size and mass of on-board tanks. That's why the solution proposed in the article, the use of hydrogen to power the existing miniature turbojet engines (e.g. GTM 400) finds its future application in terms of environment protection, and in terms of economic benefits, it can lower the price of hydrogen in the prospect of a few years it can offer economic benefits as the price of hydrogen drops [5]. That's why the solution proposed in the article, initially based on injecting hydrogen as a hybrid solution into the GTM 400 engine, will result in an innovative system developed to power the mentioned propulsion unit, so in the future it can be moved to bigger construction of aircraft jet engines.

However, it requires many tests, especially in terms of temperature distribution inside the combustion chamber and vibro-acoustics of the construction after fuel change. Tests can use the method proposed by W. Prokopowicz [8]. A hybrid method of non-invasive tests based on vibro-thermography and time analysis of stimulating signal frequency will allow testing the energy fluctuations of the burnt hydrogen under the vibrations of the combustion chamber, and the thermographic camera placed on the thermogram will confirm the energy distribution while the mixture burn inside the GTM 400 engine chamber.

A detailed process of tests, initially simulations, will allow the modified GTM 400 tests to be conducted safely. This way, it will be possible to design an optimal shape and dimensions of the injectors, develop a hydrogen distribution algorithm and determine the optimal placement of the injection system based on the size of the hydrogen distribution cone.

3. References

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