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Description of multi-fuel solutions for alternative fuel systems in turbine engines

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Multi-fuel systems powered by fuels, including alternative fuels in turbine engines, offer a modern approach to the development of this segment of devices for use in solutions such as vehicle drive systems, guaranteed power supply systems, or sustainable energy development. Thanks to the ability to operate on various fuels, such as biofuels, hydrogen, natural gas, or synthetic fuels, these engines enable greater operational flexibility and additionally reduce the emission of harmful substances. The introduction of alternative fuels allows for the reduction of CO_2, NO_x and particulate emissions, which is of significant importance in terms of the applicable exhaust emission standards and reducing exposure to air pollution. Multi-fuel turbine engines, despite the need for technological modifications and optimization of combustion processes, are becoming a key element in the aviation, energy and transport industries, supporting the transition to more ecological and efficient energy sources.

Key words: *alternative fuels, dual fuel, turbine engines, hydrogen, emissions*

1. Introduction

The classification of modern gas turbine engines is based on the use of different degrees of bypass of these units, depending on the specific application. And the needs of industry. Currently, there are two types of turbine engines: single-flow and double-flow, mainly with axial compressors. Single-flow turbines are mainly used to power training and combat aircraft. They are not very complicated and are characterized by high specific fuel consumption (1–0.8 kg/daNh) [1]. In turn, the bypass engines are characterized by a rather complicated design. At the same time, their quiet operation and economic efficiency have caused them to dominate the market as a drive for passengers and transport aircraft. The main feature of bypass engines is the relatively low specific fuel consumption of 300 g/daNh or less [1].

Jet engines can also be divided into cruising engines, in which the oxidizer necessary for the combustion process is taken from the environment, and rocket engines, which use oxidizers stored with the fuel for this purpose [2]. The design of turbine engines is based on three basic elements: the combustion chamber, the compressor and the turbine. They form the core of the engine, which is a gas generator, because hot exhaust gases are produced at the output. The air intake is located before the compressor. The compressor is connected to the turbine on one axis by means of a shaft. The air flows through the centrifugal compressor radially (at a 90° angle to the direction of flight) and must be redirected back to the combustion chamber [3]. The combustion chamber is located between the compressor and the turbine, where the fuel/air mixture is injected by injectors. After the turbine, there is a short exhaust nozzle, and finally, the exhaust gas outlet. The nozzle is usually equipped with an internal cone and has truncated walls. Much higher pressure ratios can be achieved with a centrifugal compressor that has the same frontal area. An axial compressor engine will produce more thrust for the same frontal area because air flow plays a significant role in determining thrust. The possibility of increasing the pressure ratio by adding additional stages has led to the use of axial compressors in most engine designs [3].

One of the main processes taking place in the combustion chamber is fuel combustion. It is an exothermic reaction that spreads in the space filled with substrates. It is defined as the rapid oxidation of fuels with significant heat release, characterized by a visible flame. By selecting, among others, the appropriate shape of the combustion chamber, the size of the fuel dose in the injector, and chemical additives, we can control the combustion process. The course of changes is also influenced by gas thermodynamics and heat and mass exchange [4]. The combustion efficiency in turbine engines, especially gas turbine engines, is usually between 95% and 99%, with this value depending on the type of fuel, operating conditions, combustion chamber design, and fuel injection system. Such high combustion efficiency is possible thanks to well-optimized fuel-air mixing processes and controlled combustion processes. This efficiency can be disturbed, for example, by "coking" of the injector ports, which leads to a disturbance of the flame symmetry in the combustion chamber. As a consequence, combustion occurs in turbine engines [5]:

– incomplete (the mixture cannot be completely oxidized)
– incomplete (after combustion of the mixture, unburned fuel products remain in the exhaust gases)
– complete (desirable combustion, the product is the most stable chemical compound in the reaction, e.g. CO_2).

Incomplete and incomplete combustion leads to a decrease in thermodynamic efficiency related to the conversion of internal exhaust energy into chemical energy (their ratio). Additionally, an incorrect course of the fuel combustion process in the combustion chamber of a turbine engine increases the unevenness of the temperature field at the outlet of the combustion chamber, and therefore also in front of the guide and rotor blades of the turbine of this engine. This causes these blades to overheat and, as a result, crack.

There are two basic types of combustion depending on the fuel ratio with oxidizer: kinetic and diffusion [5]. In kinetic combustion, a pre-prepared fuel mixture occurs with oxidant, which is formed before the flame front. Further on, there is the main reaction zone – the flame front, and behind it, the post-flame zone. The end of the heating and reaction initiation zone is assumed to be the point where the fuel oxidation process occurs spontaneously, without supplying heat from the main reaction zone, which roughly corresponds to the inflection point on the temperature distribution curve. In the main reaction zone, in the flame front, fuel oxidation reactions occur, as evidenced by large temperature gradients. Additionally, intermediate and final products of fuel oxidation are formed, including radicals diffusing into the heating and reaction initiation zone, starting fuel oxidation reactions [22]. The concentration distribution of individual compounds in the kinetic flame is shown below (Fig. 1).

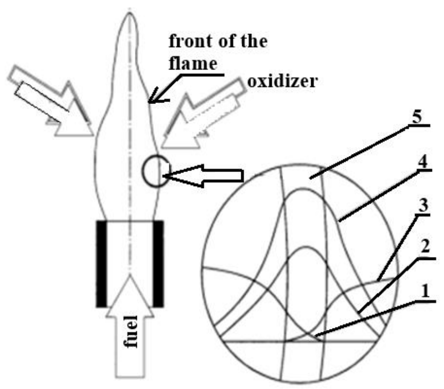


Fig. 1. Distributions of fuel: 1 – exhaust gas, 2 – oxidizer, 3 – temperature, 4 – concentration in a kinetic flame, 5 – flame [45]

In diffusion combustion, the mixing of the fuel-air mixture occurs just before combustion and lasts longer than this process. It is created in the boundary layer between the combustible gas stream and the surrounding stationary oxidizer. An example of such a flame is a candle flame, in which a glowing surface is visible, as a stoichiometric value – there is the same amount of diffusing fuel stream in relation to the oxidizer. Due to diffusion in gas streams, diffusion combustion can be divided into laminar and turbulent.

Laminar combustion is represented as molecular. The flame front's propagation speed in relation to the unburned mixture (homogeneous combustible mixture) is known as the laminar flame speed. Because it includes fundamental details regarding the diffusivity and exothermicity of the flammable hydrocarbon mixture, this attribute is crucial for a mixed flame. At a practical level, the laminar flame velocity is related to the combustion rate in the chamber, which can affect combustion efficiency and exhaust emissions. Laminar flame velocity values can be used directly in turbulent combustion models or indirectly as validation targets for chemical kinetic models. First of all, in the exhaust gas, we can find undesirable pollutants that are formed in the combustion chamber. The four primary contaminants that have been most prevalent are:

- unburned hydrocarbons (unburned fuel)
- smoke (carbon particles)
- carbon monoxide
- nitrogen oxides.

Time, temperature, and pressure are the primary factors affecting the creation of pollutants. By carrying on with the combustion to guarantee full combustion, leftover hydrocarbons can also be decreased in this zone. Air is used as an oxidant from which nitrogen in the high temperature region can react with oxygen to form nitrogen oxides. It is preferable to cool the flame as soon as possible and to shorten the period available for combustion because nitrogen dioxide gases are created under the same conditions as those needed to suppress other pollutants [31]. Figure 2 shows the dependence of the mass flow rate on the excess air flow rate.

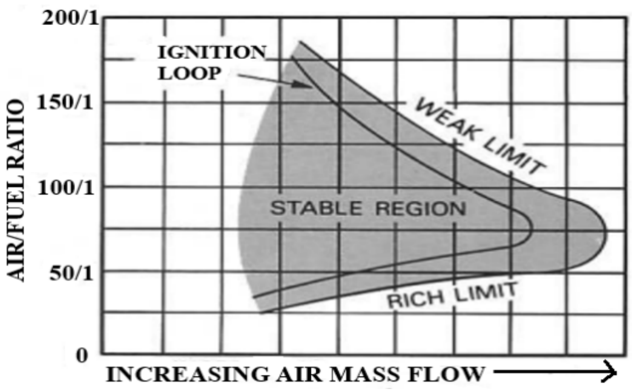


Fig. 2. Combustion stability limits [4, 7, 8]

Emissions of NO_x, CO_2, particulate matter, and many others are emitted in much smaller quantities by gas turbines compared to piston engines. The reason for this is the different combustion principle: while in piston combustion engines, thousands of individual explosions with very high cylinder temperatures generate power, gas turbines have a continuous combustion process with a lower and more uniform temperature profile.

To significantly reduce CO_2 emissions, the highest level of net efficiency is necessary, because higher efficiency reduces CO_2 emissions in grams for every kilowatt-hour produced. Heat recycling technologies are the solution to extract large amounts of energy from the still-hot exhaust gases.

Figure 3 shows that aerodynamic and industrial gas turbines have significantly lower emissions than piston engines. Apart from NO_x and CO_2, the most striking difference is the unburned hydrocarbons (UHC). Due to the explosive combustion cycle, in piston engines, unburned hydrocarbons escape through the exhaust system. This amounts to 3 to 6 g/kWh at 100% load and 13 to 40 g/kWh at 25% load. A gas turbine typically emits more than two orders of magnitude less UHC than a Reciprocating Internal Combustion Engine unit (RICE), operating at full load. Methane, which slowly degrades when released into the atmosphere, is 84 times more potent than CO_2 [27].

In order to meet exhaust emission standards, the use of alternative fuels, such as hydrogen, is becoming more and more common in turbine engines. Its injection can reduce nitrogen oxides. Combustion chambers are currently subjected to increasingly higher internal pressures, which increases the formation of NO_x. In addition, the following techniques can be used to reduce toxic compounds [19]:

- reorganization of the combustion chamber aerodynamics (so that the excess air ratio is 1:2)
- increasing the volume of the primary flame zone
- improving fuel atomization, i.e., breaking it down into smaller droplets and achieving a more even distribution.

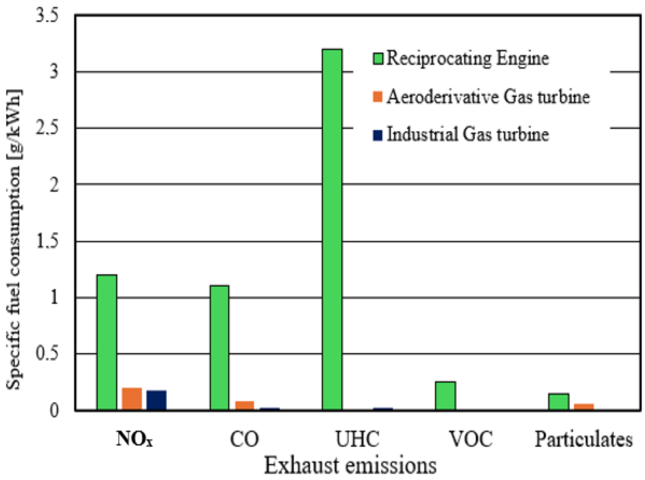


Fig. 3. Cycle combustion for different types of engines [27]

Also, in the case of catalytic combustion chambers, very low nitrogen oxide emissions below 5 ppm can be achieved. For example, the "Aquarius" type combustion chambers (named after Aquarius Engines Company) shown in Fig. 4, which combine the principle of diffusion fuel combustion and the organization of the combustion chamber with two-stage, sequential injection of superheated steam into the chamber. While energetic steam is injected separately into the combustion chamber's dilution zone to boost the mass flow rate of the working mixture, organic steam is injected into the primary zone to inhibit the production of nitrogen oxides and lower the maximum combustion temperature of the hydrogen-containing fuel.

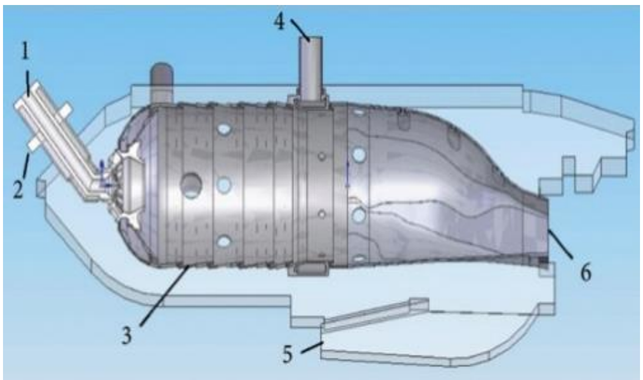


Fig. 4. Combustion chamber of an "Aquarius" type gas turbine set with steam injection: 1 – fuel supply; 2 – side steam injection; 3 – flame tube; 4 – main steam injection; 5 – air supply after high pressure compressor; 6 – gas outlet to turbine [32]

Traditionally, the most commonly used fuels for gas turbines are fossil fuels such as natural gas, jet kerosene (Jet-A), and diesel fuel. Each of these has a high calorific value and is easy to store and transport, making them ideal for high-temperature combustion processes.

In recent years, there has been growing interest in alternative fuels that have the potential to reduce greenhouse gas emissions and pollutants. These alternatives include hydrogen, biogas, and synthetic fuels made from organic waste or biomass. Natural gas is the cleanest fossil fuel source, with 30% less CO_2 emissions per kWh than oil and nearly 50% less than coal. Therefore, natural gas contributes to the reduction of carbon dioxide emissions. In addition, gas turbines can burn a mixture of natural gas enriched with H_2 in up to 100% (pure hydrogen). However, the introduction of alternative fuels is associated with technological challenges, such as adapting combustion chambers to different fuel properties, including different calorific value, energy density, or combustion temperature.

The working cycle of a gas turbine engine is similar to that of a four-stroke piston engine. In a gas turbine engine, combustion takes place at constant pressure, whereas in a piston engine, combustion takes place at constant volume. In a piston engine, only one stroke is used to produce power; the rest are involved in intake, compression, and discharge of the working fluid. Unlike an internal combustion engine, a turbine engine eliminates three "idle" strokes, thus enabling it to burn more fuel in a shorter time and producing greater power output for a given engine size.

Stability is one of the characteristics of the combustion process in the chambers of turbine engines. Flame stability is determined by two phenomena: resistance to flame decay and resistance to flashback. In the case of combustion in the chamber, the phenomenon responsible for flame instability is flame rupture. It occurs when the flow velocity is greater than the flame propagation velocity with a simultaneous lack of stabilization. Stabilization can be achieved by introducing a non-flowing body into the air stream (in the case of low-power burners) or by creating a swirling air stream. Air swirl can be created in two ways: by adjusting the air nozzles or by placing a swirler in the air stream. Other factors are the efficiency and reliability of ignition. Appropriate efficiency is achieved by the proper air to fuel ratio in the combustion mixture. In most cases, it is achieved at a level of 98–100% [2].

Another problem of the combustion process is maintaining the combustion initiation in a very stable flow, with a speed much higher than the combustion speed. To achieve the desired result, the combustion process is generated in a very stable turbulence zone (recirculation vortex), in which hot exhaust gases are mixed with a fresh fuel-air mixture. Figure 5 shows the occurrence of turbulence zones in the combustion chamber, thanks to which the combustion process can be maintained within wide limits of pressure changes, flow speed, and mixture composition. Increasing the exhaust gas flow speed causes a significant increase in thrust. The internal energy of the gases is released through the expansion process, which causes a decrease in temperature and pressure.

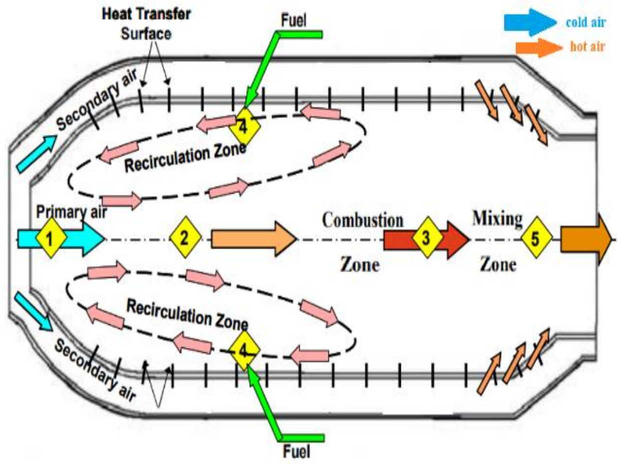


Fig. 5. Areas of occurrence of recirculation zones in the combustion chamber [29]

2. Problems with operating engines with different type of fuels

The introduction of various fuels to power engines is associated with a number of technological, operational, and environmental challenges. Traditional combustion engines, designed mainly for petroleum-based fuels, are not always adapted to work with alternative energy sources such as hydrogen, biofuels, natural gas or synthetic blends. These problems result from the different physicochemical properties of fuels, which affect combustion efficiency, pollutant emissions, and the durability of engine components.

Each alternative fuel is characterized by specific requirements regarding combustion temperature, ignition, and emission control, which require engine designers to adapt combustion chambers, injection systems, and work control systems. These problems concern engines used in land, sea, and aviation transport, where safety and efficiency are key. In the context of increasingly stringent emission standards and the pursuit of sustainable energy, solving these problems is essential for the development of ecological and efficient propulsion systems powered by various fuels, which use turbines as a driving element, used in various industries, such as aviation, energy and maritime transport, where their efficiency and efficiency are key to achieving high power with minimal fuel consumption.

In the article [41], the use of active and passive prechambers powered by alternative and conventional fuels is presented. The importance of improving combustion stability in the pre-chamber, depending on the fuel used, is emphasized. With a focus on the fuel utilized in the prechamber ignition system, this article discusses how prechamber ignition systems can optimize combustion in spark-ignition and compression-ignition engines. Among others, fuels such as gasoline, diesel, methanol, ethanol, propane (LPG), and hydrogen were studied. Figure 6 presents a comparison of energy density and specific energy for these fuels. Traditional fuels such as gasoline and diesel are among the heaviest but require the least amount of space to transport the same amount of energy as other fuels [41]. Hydrogen, the opposite of these fuels, is the lightest of them all yet also takes up the most space. Although compressed methane and liquid hydrogen are depicted in this graph, their specific energies are still quite low. In practical fuelling of combustion chambers, both specific energy and energy density are taken into account [41].

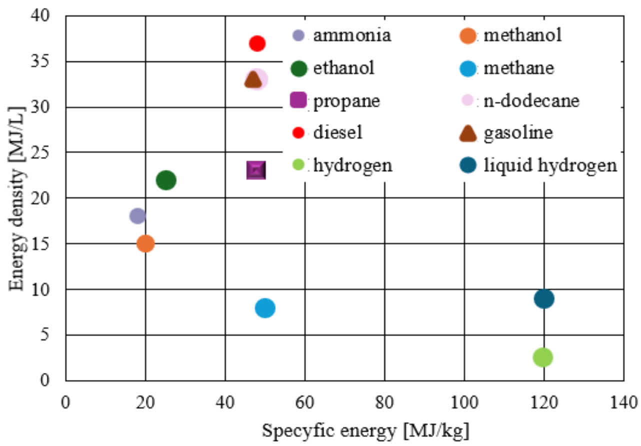


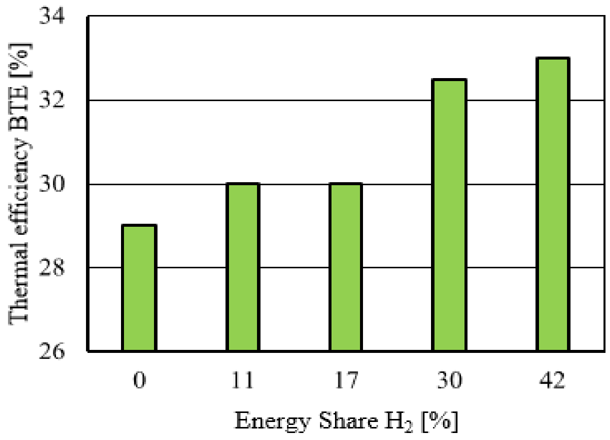
Fig. 6. Energy density and specific energy for different fuels [41]

It was found that the use of both passive and active TJI (turbulent jet ignition) fuelled with methanol was able to significantly reduce NO_x greenhouse gas emissions during gasoline operation while simultaneously increasing engine thermal efficiency [41]. TJI is an ignition technology that, unlike traditional spark ignition methods, uses a special prechamber in which the fuel/air mixture is ignited and burned in a controlled manner before entering the main combustion chamber. In SI and CI engines powered by traditional petroleum-based fuels, alternative fuels, and zero-emission fuels, knock, combustion stability, and emissions issues can all be resolved by using active and passive prechambers, according to the review's findings in this article. Fuel-specific chemical characteristics are in charge of properly starting the mixture in the prechamber, where burning of both liquid and gaseous fuels is advantageous. However, the design features of the prechamber itself that affected combustion efficiency were not described.

Article [39] presents the use of hydrogen as an internal combustion fuel for SI and ZI engines. According to the majority of research, engines that use hydrogen-enriched fuels perform better than those that use conventional fuels in terms of thermal efficiency and fuel and energy consumption. Additionally, reductions in exhaust emissions such as smoke, soot, HC, CO, CO_2 and NO_x can be achieved in both ZI and SI engines, under appropriate operating conditions. Moreover, better combustion correctness was observed in both hydrogen-fuelled internal combustion engines. These improvements were mainly attributed to the physicochemical properties of hydrogen, which exhibits a higher calorific value and high flame speed [39]. Adding hydrogen fuel to the conventional engine improved engine performance. The relationship between hydrogen energy share and specific energy consumption (BSEC) and thermal efficiency (BTE) is depicted in Fig. 7. It can be stated that the thermal efficiency improved after adding hydrogen to a limited extent. The highest BTE was observed at 20% for both 50% and 60% hydrogen content in dual fuel mode at 80% load condition [39]. However, since hydrogen fuel has a higher energy content than ordinary diesel, the BSFC and

BSEC values declined as the hydrogen substitution ratio and load increased.

a)



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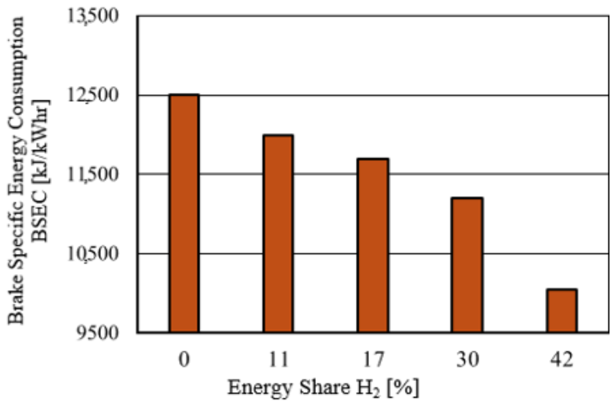


Fig. 7. Variability: a) BTE, b) BSEC based on the proportion of hydrogen energy [39]

In conclusion, under the right operating circumstances, the use of hydrogen in combustion engines has improved engine performance, exhaust emissions, and combustion behaviour, as well as other engine adjustments like the ignition system and, for instance, the SI engines usage of iridium spark plugs. As shown by most studies, thermal efficiency was significantly improved by the addition of hydrogen in both SI and CI engines [39]. When pure hydrogen was utilized as the engines only fuel, this occurrence also happened. Moreover, hydrogen-diesel blended fuels typically displayed lower values for fuel and energy consumption in SI and CI engines, as measured by BSFC (brake specific fuel consumption) and BSEC (brake specific energy consumption), respectively, when compared to traditional fuels. The breakthrough in engine performance was primarily attributed to the unique properties of hydrogen fuel with a higher calorific value and high flame speed, which supported the combustion process [39]. However, it was also observed that the decreased density and volumetric efficiency of hydrogen fuel caused a decline in performance in the case of SI engines.

In another article [17], self-ignition characteristics of various alternative fuels (vegetable oil, diesel oil with additives, etc.) in dual-fuel mode with hydrogen, ammonia, and methane addition were described. At 535°C and 600°C, the fuels were tested in a constant-volume combustion chamber. Delay times were the primary markers of self-ignition behaviour (IDCF). This was the amount of time that passed between the beginning of the injection and the point at which the pressure rose by 0.2 bar above the starting pressure. The point at which the line joining 1/2 and 1/4 of the maximum pressure (dP/DTmax) equals zero was determined to be the major self-ignition delay time (IDM) [16]. The fuel containing ethers (20% biodiesel in the mix with diesel) is the most sensitive. In contrast, the type and level of low-reactivity fuels (LRF) have a less significant impact on biodiesel, as shown in Fig. 8. Consequently, as the amount of LRF increases, so does the ignition delay time. In terms of the impact of the liquid fuel's chemical structure, biodiesel was least impacted by the presence of LRF because it had a higher proportion of secondary to primary carbon and hydrogen covalent bonds and allyl and bis-allyl groups. In contrast, the blend (20% biodiesel) was highly sensitive to the type and amount of LRF because it had a more balanced branching ratio and a lower dissociation energy of carbon and hydrogen covalent bonds (C–H) than saturated hydrocarbons. The findings demonstrated that, in addition to the previously known absorption effect, adding ammonia to diesel fuel had a greater impact on the autoignition time than did methane (CH_4) and hydrogen (H_2). It also contributed to the formation of stable intermediates (N_2H_4), the latter slowing down the chain branching reactions.

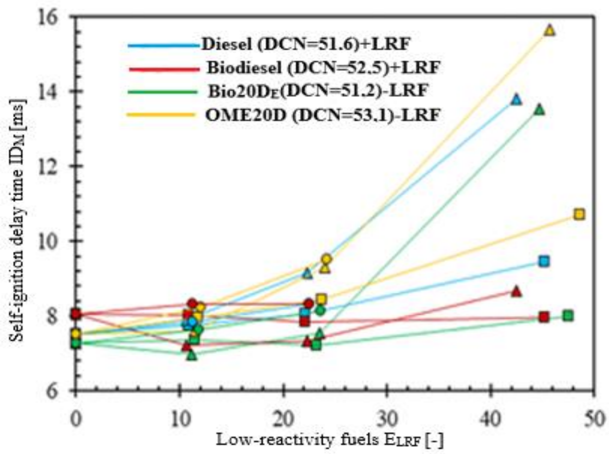


Fig. 8. Diesel and biodiesel's primary ignition delay times, BIO20D and OME20D with H_2, NH_3 and CH_4 additives [17]

Two distinct approaches to using alternative fuels and meeting the EURO criteria in diesel engines are described in article [11]. Various amounts of diethyl ether were added to the biodiesel fuel in the study's initial phase. In order to attain NO emissions from exhaust gases at the level of the EURO standard, the intake manifold was equipped with an EGR rate of 10% in the second stage of the study. Through the transesterification process, corn oil was converted into the biodiesel used in the study. In amounts of 2.5%, 5%, and 7.5%, diethyl ether was added to the biodiesel [11]. The percentage changes in torque with varying amounts of diethyl ether additives in comparison to diesel fuel are shown in Fig. 9. Engine torque is found to diminish when diesel engines run on biodiesel as an alternate fuel. According to the graph analysis, torque decreased at all engine speeds when biodiesel made from corn oil was used in place of diesel fuel. The torque dropped by a maximum of 4.6% at 1200 rpm. The reason for the reduction in torque is the fact that the lower calorific value of biodiesel than diesel fuel causes a decrease in the energy supply to the combustion chamber [11].

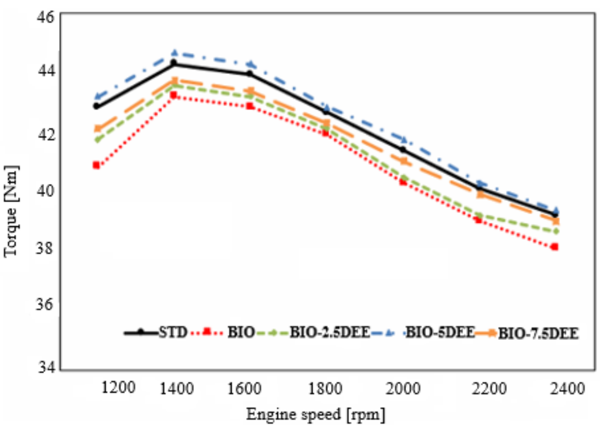


Fig. 9. Torque–speed graph of biodiesel with diethyl ether added [11]

Dimethyl ether (DME) is a possible contender in the upcoming years as an alternate fuel to natural gas and diesel fuel in gas turbine applications. Both natural gas and coal/biomass gasification can yield this chemical compound. In diesel engines, DME works well as an alternative to diesel fuel. Although it has a lower heating value than ethanol, it has certain advantages over alcohols in terms of stability and hydrocarbon miscibility.

In published work [15], the aim of the problem is to investigate the combustion behaviour of DME under gas turbine conditions by means of detailed kinetic modelling. Several important combustion parameters were investigated, such as autoignition temperature, ignition delay times, laminar combustion velocities of premixed flames, adiabatic flame temperatures, and the formation of pollutants such as CO and NO_x [15]. These figures were contrasted with methane combustion calculations. A well-established process from the literature that has already been applied to forecast the behaviour of other alternative fuels served as the foundation for the model's construction. Formaldehyde is the primary intermediate product that DME produces under flame conditions; its consumption eventually results in CO and CO_2. Rapid NO production appears to be less likely when there are fewer CH_2 radicals present than in methane flames. In order to accurately forecast ignition temperatures and autoignition delay times, two crucial safety parameters are needed. This research discusses the oxidation chemistry of DME at low temperatures. Regarding NO formation, there is not much difference between the mole fractions calculated for DME and methane. This result is consistent with the fact that the adiabatic flame temperature of DME is only slightly higher than that of methane [15]. The primary cause of DME's higher reactivity than that of methane and bigger alkanes is its propensity for a quick reaction with oxygen to create formaldehyde, according to an analysis of the several DME consumption pathways.

A survey of hydrogen- and other fuel-mixed combustion engines can be found in the article [42]. In recent years, some researchers have combined hydrogen with biogas (primarily CH_4 and CO_2), dimethyl ether (DME), methane (CH_4), or other low-heat gases (primarily CNG, N_2, and CO_2) and used them as fuel in engines in addition to hydrogen as an additional fuel in gasoline, diesel, natural gas, and alcohol engines. Because they contain a lot of inert and low-flammable components, gases with lower heating values, like biogas and coal bed methane, are hard to ignite steadily. The creation of hydrogen-doped gas engines with a lower calorific value, however, has garnered a lot of scientific interest from engine development experts because of the special qualities of hydrogen [42]. The fact that hydrogen doesn't contain carbon and doesn't release carbon pollution is its greatest benefit. It should focus on researching engines that run on pure hydrogen in order to fully address the issue of hazardous emissions from engines. The pure hydrogen-fuelled engine's air intake system is primarily separated into two sections: manifold injection and direct injection. In the case of hydrogen-powered engines with downstream injection, when the hydrogen and air are mixed at the intake, they will occupy part of the engine working volume (air displacement effect), especially under stoichiometric conditions, even though those engines with intake manifold injection are the most efficient, cost-effective, and dependable way to use hydrogen energy [42]. The limited power of hydrogen engines is one of their drawbacks. For instance, one study examined the impact of adding a low calorific value gas with hydrogen admixture to a modified single-cylinder CNG engine on performance. The findings demonstrated that increasing the amount of nitrogen could result in higher HC emissions while decreasing engine power, CO, and NO_x emissions. Additionally, it was discovered that raising H_{vf} (hydrogen volume fraction) decreased HC emissions while increasing CO emissions, maximum power, and engine torque; however, a large H_{vf} would result in a decrease in engine power [42].

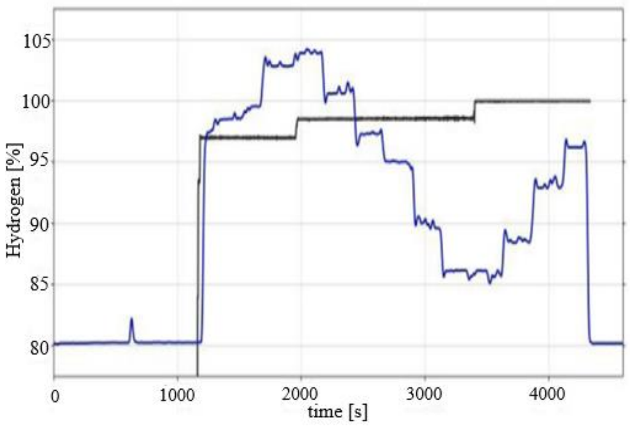
Another important issue is the powering of gas turbines with hydrogen alone. In the article [5] hydrogen was integrated as an energy carrier into the energy system. For this purpose, a micro gas turbine powered only by hydrogen was designed, with NO_x emissions below the standards. Because of their dependability and quick response to network load variations, microturbine gas engines (MGT) with capacities ranging from 3 to 300 kW are essential to decentralized power generation and make an excellent backup for intermittent renewable energy sources. MGT's status as a power generator is further reinforced by its weight, small size, and inexpensive installation and maintenance expenses. In the foreseeable future, in the distributed energy system [5]. Commercial engines like the Turbec T100 PH gas microturbine can generate heat and energy. A single tubular combustion chamber, a single-stage radial turbine, and a single-stage centrifugal compressor make up the engine. It works using the regenerative Brayton cycle, which transfers heat from the hot gas exiting the turbine to the air entering the combustion chamber through a recuperator. The engine has a gas/water heat exchanger in addition to the recuperator, which heats the flowing water using the heat that is still present in the exhaust gases [5]. The permanent magnet generator used in the engine allows it to operate at variable speed. Figure 10 shows a view of the microturbine station equipped with a modified combustion chamber adapted to burn pure hydrogen.

Fig. 10. Turbec T100 PH microturbine system [5]

An external compressor supplied the required pressure increase because the engines' original fuel system was built to run at low pressures. However, a new method that incorporates fuel sources like hydrogen accumulators and methane stored in a bundle structure took the place of this one. As a new component of the engine, the combustion chamber is also fitted with sensors to continuously monitor its status throughout the test in an effort to prevent excessive material temperatures. Both before and after mixing, the characteristics of methane and hydrogen are measured. The temperature of the fuel supplied to the combustion chamber is measured using a thermocouple that is mounted inside the chamber. A gas analyzer that detects the concentration of different components is placed in order to evaluate the impact of hydrogen injection on CO and NO_x emissions. The exhaust gas path has the analyzer probe fitted. A measuring set is used to measure exhaust gas emissions (NO_x, CO, and CO_2) during the measurement phase. The tiny gas turbine operated steadily during the testing, with NO_x emissions falling within the permitted limits, and the fuel's volumetric hydrogen content varied from 40 to 100% [5]. For full load operation and pure hydrogen, the maximum NO_x emission measured was 22 ppm, or 62 ppm adjusted using the reference value of 15% oxygen in the exhaust stream. The stability of the micro gas turbine while satisfying regulatory NO_x emission criteria is demonstrated by a comprehensive range of data for operation with varying hydrogen contents (Fig. 11) [5].

A small gas turbine powered by methane-hydrogen fuel must be powered without experiencing flashbacks or excessive temperature rises. An autonomous internal exhaust gas recirculation (IFGR) system was suggested in this paper [11] as a solution to the aforementioned hydrogen combustion issues. The exhaust gas recirculation system's working principle, suggested design, and impact on emissions (CO and NO_x) and combustion chamber operating parameters were all discussed. A portion of the exhaust gas could be moved from the combustion chamber outlet zone to the top section of the liner thanks to modifications made to the combustion chamber.

a)



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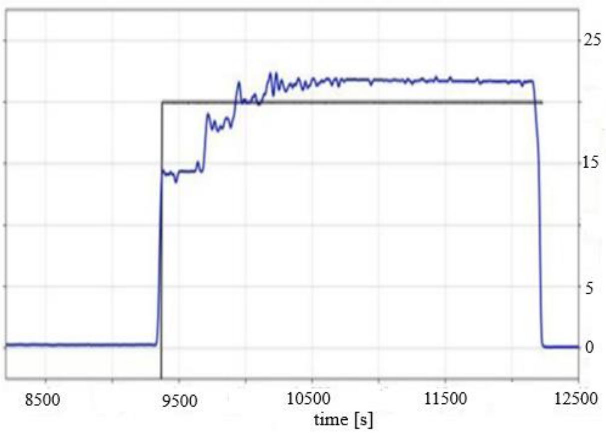

Fig. 11. Hydrogen content (a) and NO_x emissions (b) during engine operation using 100% hydrogen [5]

Exhaust gas recirculation uses the difference between the static pressure at the top section of the liner and the total pressure at the combustion chamber exit. Ansys software's CFD analysis served as the foundation for the simulations used in this investigation. The simulations took into account the following processes that took place in the computational domain: radiative heat exchange, unmixed combustion in the gas phase, and turbulent flow.

Figure 12 shows that the mass flow of recirculated exhaust gases is insufficient to have the anticipated impact on the combustion processes. The alteration of the air-fuel equivalence ratio during combustion is the cause of the observed variations in temperature and pollutant concentration. Gieras [14] introduced the idea of modifying the insert holes to maximize a microjet turbine's combustion process. This effectively modifies the mass flow through the chamber under various operating conditions. By generating or enlarging the combustion zone with an air-fuel equivalence ratio around unity, an internal exhaust gas recirculation system (IFGR) can be introduced into the combustion chamber and alter the combustion process. This event could cause the rise in combustion temperature. The combustion process in a micro gas turbine does not appear to be improved by the autonomous IFGR technology. If the mass flow of recirculated exhaust gas were increased, for instance, by adding another pumping system, this idea would function, but power losses would ensue [12].

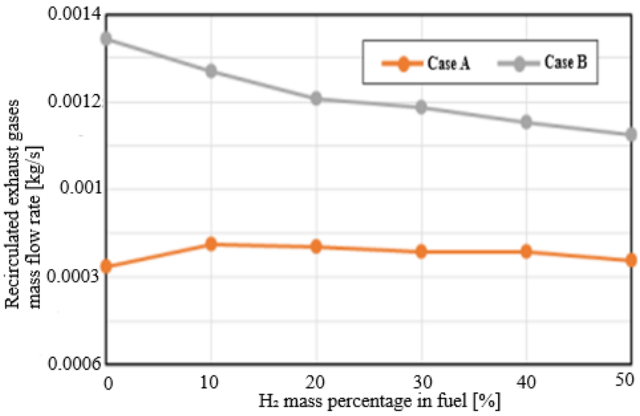

Fig. 12. Recirculated exhaust gas mass flows [12]

By choosing for example the right shape of the combustion chamber, fuel flow through the injector and chemical additives, it is possible to control the combustion process [13]. The combustion efficiency of most turbine engines under takeoff conditions is almost 100 percent, decreasing to 98 percent under high-altitude cruise conditions. This efficiency can be disturbed, for example, by "coking" the injector openings, which leads to a disruption of the symmetry of the flame in the combustion chamber. Therefore, there is incomplete combustion and total combustion in turbine engines.

It's important to consider the automobile sector when evaluating hydrogen's potential as a fuel of the future. Compared to turbine engines, piston engines are characterized by greater flexibility in the use of hydrogen, as well as easier adaptation to existing engine designs. For this reason, combustion engines have more applications for hydrogen supply. Research on automakers, which has been going on for nearly ten years, is one example from the sector. The Japanese automaker Toyota Group has been working on this technology for years after realizing the potential of hydrogen fuel in 2014. In the Mirai model, an electric motor is powered by electricity produced by a hydrogen fuel cell. A hydrogen-based fuel cell in this vehicle (FCV, or fuel cell vehicle) mixes hydrogen with ambient oxygen to produce heat, power, and water as byproducts. There are two tanks for compressed hydrogen under the floor. It results from the use of fuel cells, which do not affect the size of the vehicle. This means that cells can also be used in semi-trucks, off-road vehicles and even in airplanes. The Toyota Mirai can travel 482 km with one full refuelling (lasting about 3 minutes) [44]. The problem of the tank's tightness was solved in several ways. The inner layer of the tank was made of plastic. This guarantees tightness by preventing the diffusion of tiny hydrogen particles through the walls. The middle layer was made of a composite reinforced with carbon fibre. Thanks to this, the cylinder is resistant to pressure many times greater than that which prevails inside the tank (approx. 700 bar). The outer layer was made of a composite reinforced with glass fibre, which protects the tank from mechanical damage [45].

In the beginning, hydrogen-gasoline mixtures were made by hydrogen combustion. Numerous reasons contribute to this, such as a significantly higher rate of flame propagation, a difference in the mixture equivalence ratio φ, and a far lower energy need for ignition, which causes combustion to knock. This issue is covered in detail in [24], which also discusses the benefits of employing a pre-chamber as a combustion control technique and shows how the mixture equivalency factor and compression ratio affect knocking combustion (Fig. 13). A lean mixture lowers the chance of knocking combustion because it helps to slow down the rate at which the flame spreads. Learning the combination is desired since studies have shown that a stoichiometric mixture has the highest hydrogen intensity. For a 50% hydrogen component in the mixture, this results in a corresponding 25% engine power reduction. Subsequent phases saw more achievements with pure hydrogen fuel kept in a high-pressure tank, followed by tanks for liquid and intermediate gaseous hydrogen. On the other hand, studies show that hydrogen and diesel blends greatly improve the mean effective pressure.

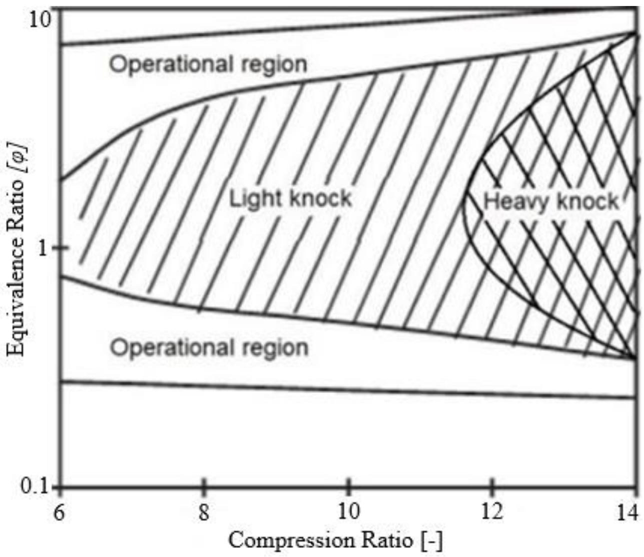

Fig. 13. Hydrogen combustion regions in SI engines [24]

The low power density of hydrogen compared to other fuels, such as gasoline or natural gas, further highlights the challenges associated with its use as a fuel source [3]. Furthermore, certain materials may get embrittled by hydrogen, endangering the structural soundness of transit and storage networks. It is very important to ensure the material's compatibility with hydrogen. Moreover, energy is wasted during the conversion process when hydrogen is utilized in fuel cells to produce electricity, which lowers the total power density of hydrogen-based systems [3]. The broad range of hydrogen's flammability in air, which varies from 4% to 75% by volume, presents another difficulty. This indicates that, compared to fuels with lower flammability restrictions, hydrogen is more prone to ignition. Furthermore, hydrogen can be ignited by low-energy sources like sparks or heated surfaces because of its low ignition energy threshold. Therefore, reducing the number of ignition sources is essential for safety when handling hydrogen. Lastly, a hydrogen explosion can produce a shock wave that travels at extremely high speeds, seriously damaging equipment and buildings. Consequently, any hydrogen project must control and reduce the risk of detonation [3]. Engine parts may wear down and sustain damage as a result of the high temperatures and pressures involved in hydrogen combustion. Furthermore, hydrogen's low density causes problems in fuel injection systems, and its reactivity increases the risk of corrosion. Special materials are utilized in engine parts that are subjected to high pressures and temperatures in order to overcome these difficulties. Additionally, to lessen the possible impacts of corrosion, components exposed to hydrogen are made of materials that are resistant to corrosion. It is advised to use premium fuel and oil with low sulphur content and few contaminants. Hydrogen fuel is a better additive for gasoline engines than diesel engines due to its high autoignition temperature. Certain ratios of hydrogen to gasoline can raise the engine's compression ratio, enhancing performance and economy. Depending on how much hydrogen is added to the fuel, studies have indicated that hydrogen enrichment can enhance gasoline engines' performance and fuel efficiency. Furthermore, gasoline engines are better suited for hydrogen enrichment due to their structural characteristics, which lowers emissions and fuel consumption [3]. However, hydrogen cannot be used directly in diesel engines due to its high flash point. Researchers have therefore created a number of techniques for adding hydrogen to the cylinder.

Hydrogen is fed straight into the combustion chamber using the direct injection technique. Several stages of the engine cycle can be used for this process:

- hydrogen is injected during the intake stroke, allowing for better mixing of fuel and air
- hydrogen is injected at a later stage (compression), which allows for better control of the ignition and combustion timing.

The advantage of this method is precise control of the amount of hydrogen introduced and better control over the combustion process. The biggest disadvantages include the level of advanced injection technology and expensive components.

Another method of hydrogen supply is to supply a mixture of air and hydrogen indirectly (port fuel injection). Hydrogen is introduced into the intake manifold, where it is mixed with air, and then the mixture is sucked into the cylinder. This is a simpler technology compared to direct injection. It is also characterized by lower implementation costs. However, there is less control over the fuel-air mixture. Pre-ignition is possible.

There is also the possibility of hydrogen supply through a carburettor. Hydrogen can be supplied to the engine by a specially designed carburettor that mixes hydrogen with air before it is supplied to the cylinders. The advantages include lightweight construction and low costs compared to injection systems. The disadvantages include difficulties in precise control of the fuel mixture and fewer possibilities of regulating the combustion process [36].

Some systems use solutions that allow switching between hydrogen and other fuels, such as gasoline or natural gas. These engines can be equipped with dual injection or fuel mixing systems. The main benefits of dual power systems are: flexibility in fuel selection and the ability to use alternative fuels in the absence of hydrogen. The disadvantages include a more complicated design and the need for an advanced fuel management system. Additionally, in industrial applications, hydrogen can be produced on site using fuel reformers that process hydrocarbons into hydrogen. A positive feature is the ability to produce hydrogen directly on site, as well as potentially lower hydrogen transport costs. A disadvantage is the complex technological process. It requires additional equipment and infrastructure. Each of these methods has its specific applications depending on the type of engine, technological requirements, and implementation costs. The selection of the appropriate method of introducing hydrogen into the cylinder depends on many factors, such as efficiency, costs, technology availability, and specific application requirements.

An overview of the current state of knowledge on hydrogen combustion systems is provided in article [24]. These systems are now the most appealing development path because of their well-developed production technology and comparatively low recycling costs when compared to fuel cells. Experience demonstrates that knock combustion is quite likely to occur even with a high self-ignition temperature and hydrogen resistance to compression, which are caused by a high octane number (RON > 130). The low ignition energy of hydrogen and the fact that the octane number is an inappropriate metric to characterize the characteristics of gas fuel appear to be the causes of this problem. According to research, Ryan's so-called methane number [25] is a far better indicator of the likelihood of engine knock combustion during hydrogen combustion. This parameter describes the percentage of methane in the reference hydrogen mixture. Of all the fuels, hydrogen has the greatest methane number. The intensity of pressure pulsation is described by a metric called knock combustion intensity, which is thought to be between 20 and 100 kPa in the case of light knock. The impact of combustion intensity on the compression ratio is depicted in Fig. 14. Following the self-ignition zone, the compression ratio quickly rises in tandem with the increase in combustion intensity.

In hybrid systems, fuel cells are starting to compete more and more with piston combustion engines. Nevertheless, hydrogen fuel cells are still too costly to manufacture and problematic to use at this point in their development. Consequently, hydrogen may be effectively utilized as fuel for contemporary piston combustion engines during the changeover phase. This will enable, among other things, the establishment of a network for refuelling hydrogen-powered vehicles and acclimating consumers to the new fuel [7]. This article describes the development of novel techniques for supplying hydrogen to internal combustion piston engines, which allow for the regulation of heat release during combustion. Low nitrogen oxide emissions and favourable engine operating characteristics were ensured as a result of this work.

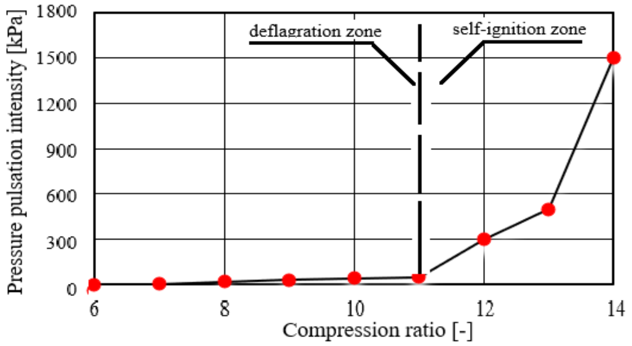

Fig. 14. The influence of the compression ratio on the intensity of pressure pulsation [25]

The tests were performed on a modified Kipor186F engine adapted to spark ignition and hydrogen injection. Measurements of nitrogen oxide concentration were performed while the engine was supplied with a hydrogen-air mixture of different composition (air excess coefficient). At each of the selected engine operating points, the start of hydrogen injection into the cylinder was selected so as to obtain the highest value of hydrogen injection into the cylinder in order to obtain the highest torque value or the lowest nitrogen oxide concentration value (Fig. 15).

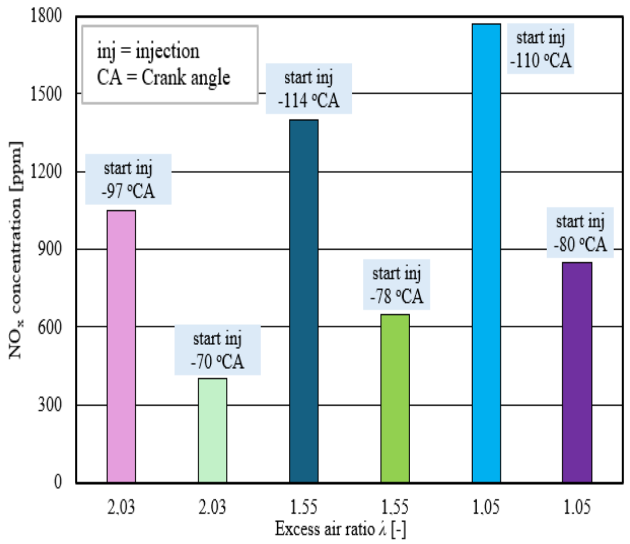

Fig. 15. Nitrogen oxide concentration at specific engine operating points [7]

This technique made it possible to burn a mixture with a stoichiometric composition without experiencing uncontrolled spontaneous combustion, combustion anomalies, or uncontrolled combustion. Both the instantaneous value of the cylinder pressure increase and the pace of heat release can be controlled. The findings indicate that nitrogen oxide creation is influenced by higher pressure, and that the rise in the instantaneous cylinder pressure has a stronger effect on nitrogen oxide formation than the mix's oxygen content [7].

A five-component model and six single-component alternative fuel models are systematically evaluated in the study [43] in order to use large eddy simulation (LES) to forecast the spray properties of biodiesel under various situations. The significantly different physical properties and combustion characteristics of biodiesel compared to traditional diesel fuels cause its combustion process to proceed differently [34]. The spray process of biodiesel in a constant volume (CVV) tank under normal engine running circumstances was examined in this study using LES. Below is an illustration of the spray plume's calculation cells and simulation models (Fig. 16). In the centre of the cylinder head, an injector with seven nozzle holes was positioned axially symmetrically [43].

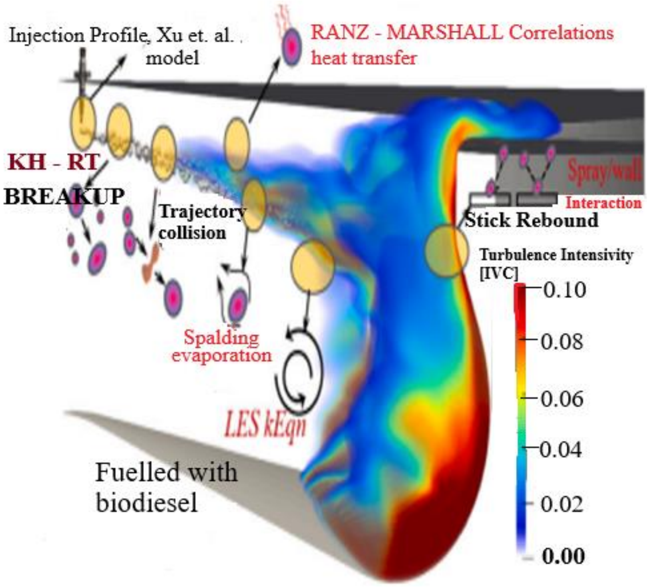

Fig. 16. Simulation models used in engine operation modelling [43]

By compressing and extending the grid in the crush region, Open FOAM simulates piston action while maintaining a constant total number of grid cells in the computational domain. The simulation's CCM approach calculates the reaction rates for cell assemblies using a six-dimensional chemical phase space that comprises the mass fractions of hydrogen elements and fuels, temperature, scalar dissipation rate, and equivalency factor.

A novel idea for a pressure-gain combustion (PGE) turbine engine was introduced in the article [38]. The idea effectively addressed the issues with the accurate timing of the combustion chamber's opening and shutting. In order to effectively convert high-pressure gas energy into mechanical energy, the suggested valve timing system produces ideal gas flow. The adoption of an efficient sealing system was made possible by rotating combustion chambers. The straightforward design and possibly low power-to-weight ratio set it apart. Low specific fuel usage and extremely promising efficiency were demonstrated by a CFD simulation study. With a potential low power-to-weight ratio, low fuel consumption of 219.9 g/kWh, and significant effective energy efficiency of 37%, the hybrid gas turbine engine concept that has been presented is a promising project. Compared to similar engines with isobaric combustion, its straightforward design can lower production costs. Although a crankshaft is not required, it shares some parts with piston engines, such as fuel injection systems and turbochargers. Rotating combustion chambers can be sealed with an efficient ceramic system.

3. The impact of combustion on pollutant emissions

In traditional diesel engines, it is possible to use biodiesel and biodiesel-butanol blends, which are characterized by high combustion efficiency and low CO and UHC emissions. In contrast to pure biodiesel, which necessitates an early injection and low injection pressure to guarantee the proper combustion phase around TDC, the fuel mixture's ignition delay time is greater. CDC engines that use a combination of butanol and biodiesel have high NO_x emissions [43]. The research discussed in this article benefits from the usage of biodiesel, and reactivity-controlled compression ignition (RCCI) engines can use butanol to obtain low NO_x emissions. Because of their lower and more consistent temperatures, RCCI engines encourage less heat loss to the walls. High CO emissions and poor combustion efficiency are a problem, though.

Another type of dual fuel supply can be the combustion of natural gas and diesel oil (NDDF) [20]. An economical and versatile method to achieve reactivity-controlled compression ignition (RCCI) mode has been developed by installing additional gas fuel injection and control equipment at the intake. This method can ignite the fuel-air mixture by means of highly active diesel fuel injectors in the cylinder, which simultaneously reduces combustion noise and increases the engine load range. Figure 17 shows the graphical diagram of the measurement system. A controlled supply system is used at the intake port to inject natural gas to achieve NDDF mode.

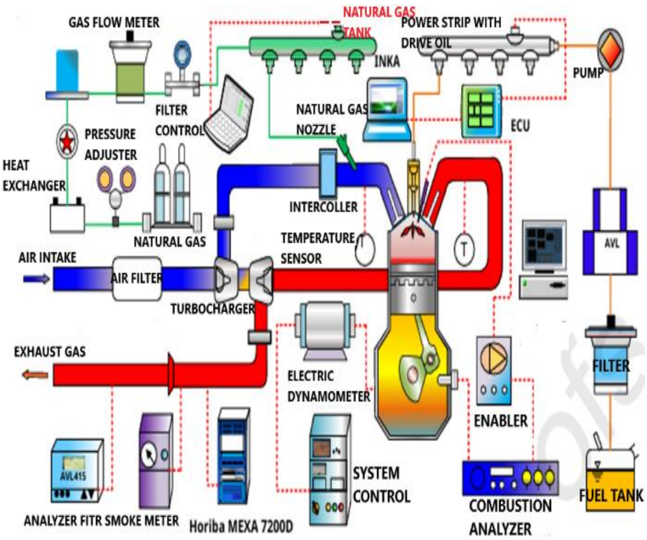

Fig. 17. The measurement system diagram used to test the NDDF supply [20]

Giving the pilot dose of natural gas causes the reactive groups in the cylinder to build up before the main diesel fuel injection burns, increasing the gas fuel's ignition surface, speeding up the mixture's combustion, improving combustion efficiency, and continuously raising the cylinder's internal pressure and temperature, all of which increase NO_x emissions. Furthermore, pilot injection diesel fuel's increased heat release raises the combustion chamber's temperature and lengthens its duration, resulting in a more complete burning of the flammable mixture and facilitating additional soot oxidation. As a result, there is a significant decrease in carbon monoxide and hydrocarbon levels [20].

Natural gas has become a viable alternative fuel in light of the growing concerns about energy and environmental conservation. Using natural gas in engines in dual fuel mode with diesel and natural gas is more economical and feasible. Alternative fuels are playing an increasingly important role in the pursuit of sustainable energy and reducing emissions. The introduction of biofuels, synthetic fuels, hydrogen, and fuel blends to combustion engines, including turbines, allows for the reduction of harmful emissions such as CO_2, NO_x, and particulate matter. Although some of these fuels require technological modifications and optimization of combustion processes, their use brings benefits both in the context of environmental protection and energy efficiency. With the ability to run on a variety of fuels, such as biofuels, synthetic fuels, hydrogen or natural gas, these engines offer flexibility in selecting energy sources, which can contribute to increased energy security and reduce dependence on traditional fossil fuels. Despite some technical challenges, such as the need to adapt injection systems and optimize combustion processes, multi-fuel propulsion systems have the potential to reduce CO_2 emissions and other harmful substances significantly. In the long term, they can play a key role in the energy transition, promoting a cleaner and more diverse approach to fuel use.

A thorough experimental examination of the impact of the hydrogen energy content ratio and various combustion techniques, including exhaust gas recirculation, diesel injection pressure, and diesel injection characteristics, was conducted in the study [10]. Additionally, the use of hydrogen fuel in a heavy-duty hydrogen-diesel dual-fuel engine at low and medium operating loads was examined. Engine operation with an H_2 energy level of up to 98% was accomplished under low-load situations without affecting engine performance [10]. Compared to traditional running on diesel alone, this situation offered a simultaneous reduction in carbon and NO_x emissions of over 90% and soot emissions of 85%. The primary issue at medium load was the elevated NO_x emissions brought on by the hydrogen's high energy content.

An alternate method of reducing dangerous NO_x emissions from engines is to use improved injection and combustion techniques. Exhaust emissions can be significantly reduced by using several injection schemes and the best injection timing, as demonstrated [10]. While late injections of diesel fuel might impair engine performance and fuel consumption, early injections can result in a significant rise in cylinder pressure and NO_x generation. A lean mixture was created, where the diesel fuel served as the ignition source for a variety of cylinders, thanks to the Pre-Mixed

Charge Compression (PCCI) combustion technique, which gave the diesel fuel enough time to mix with air and hydrogen before ignition. As a result, the heat was released smoothly, and the combustion was extremely sluggish. However, only low equivalency ratios and, most likely, unstable combustion characteristics can be used with early diesel inputs. Additionally, the performance and emission production of compression ignition engines are significantly impacted by the diesel injection pressure. It is anticipated that the diesel pressure will continue to be crucial in regulating engine performance and emissions even when a portion of the diesel fuel is substituted with H_2 fuel in dual fuel mode.

In light of these nitrogen oxide reduction initiatives, the proposed study [23] will examine the effects of lowering CO_2 and NO_x levels under normal operating settings by concentrating on the usage of hydrogen and hydrogen fuel mixes in an aircraft engine's combustion chamber. H_2 is one of the most promising fuels for the aviation sector to drastically lower CO_2 levels, along with other Sustainable Aviation Fuels (SAF). However, with a hydrogen-air combustion engine, NO_x emissions are more problematic. When hydrogen is the main fuel, it becomes even more challenging to comprehend NO_x emissions, their quantities, and the temperature distribution in the combustor. More details on the temperature distribution and NO_x emissions should be available from numerical combustion simulations that accurately depict chemical kinetics, which will aid in combustible engine design. There isn't much computational research being done in the gas turbine field right now. This research performs many computational fluid dynamics (CFD) evaluations for the NASA published gas turbine combustor shape under two different fuel flow conditions by altering the combination of hydrogen and methane mass fractions in the fuel mixture. The primary purpose of all earlier computations was to examine the fuel-air mixing characteristics in non-reacting scenarios. In 25% increments, the mixture's hydrogen content was changed from 0 to 100% (all methane to all hydrogen). Reaction flow models for both pure hydrogen and a 50/50 CH_4 mixture were carried out in this work, and the outcomes were explained and shown. All reaction flow calculations were performed using Converge CFD software (Fig. 18), which employed the NASA reference combustor geometry at the combustor inlet circumstances at the design stage. The available experimental data on emissions and combustion efficiency are examined together with numerical results.

Based on its energy properties, the use of hydrogen fuel for turbojet engines presents a distinct challenge. To gauge the assessment of the turbojet engines' energy statistics, a study [16] was carried out. First, Jet A-1 fuel was used for the test. The performance of turbojet engines running on hydrogen fuel was then assessed through a battery of comparable tests. Lastly, a comparison between the two exergy values was made. Energy efficiency decreased with the introduction of hydrogen fuel, and a ten percent decrease was noted. Meanwhile, there was a 9% increase in the waste exergy rate. However, hydrogen fuel was superior to Jet A-fuel because of its high energy content. It should be mentioned that the addition of hydrogen resulted in an increase in metrics like the ecological effect. In order to reduce CO, NO_x, and CO_2 emissions from gas turbine engines without sacrificing efficiency, alternate blends must be introduced. Blends were used in place of Jet A fuels in order to improve emission characteristics. The usage of hydrogen negatively impacted the energy performance of turbojet engines. On the other hand, the 200 percent reduction in emissions was really impressive. Because of its irreversibility, the combustion chamber has the greatest values of exergy coefficient, waste exergy coefficient, cost flow, ecological coefficient, environmental coefficient, and fuel composition when the exergy efficiency results of the input, combustion, and nozzle are compared.

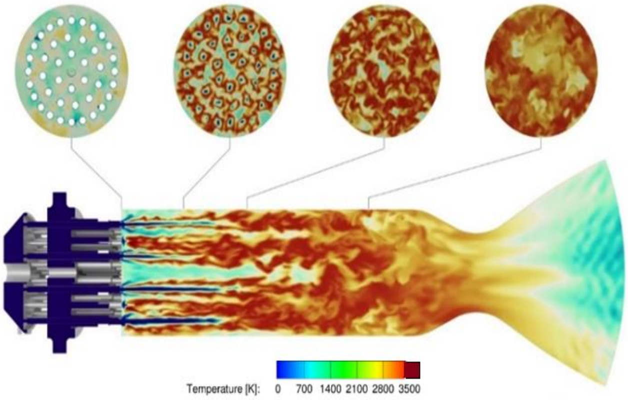

Fig. 18. Example of using Converge software for CFD analysis of a combustion chamber [8]

The use of hydrogen as a fuel in the aviation industry has emerged as a promising solution to the environmental challenges associated with conventional hydrocarbon fuels. Hydrogen, as a clean and sustainable energy carrier, has the potential to significantly reduce emissions and contribute to a more sustainable air travel ecosystem. Article [30] focuses on investigating the feasibility and potential benefits of using hydrogen as a fuel in the GE90 turbofan engine, which is widely used in commercial aircraft. commercial aircraft. The results were developed using MATLAB, a computational modelling tool, and an analysis of engine performance under hydrogen combustion conditions. Various factors are considered in the simulation, including thermodynamic properties, combustion characteristics, and performance parameters specific to the reference engine. By simulating the engine behaviour and performance, the research aims to evaluate the potential impact of hydrogen fuel on various performance parameters, including thrust generation, engine efficiency, emission profile, and other relevant factors.

In addition, the thermodynamic properties of the fuels play an important role. Hydrogen fuel has a higher specific heat (c) compared to hydrocarbon fuels. The specific heat ratio is a measure of the amount of heat energy that can be added to a substance per unit mass without causing a phase change. The higher specific heat ratio of hydrogen fuel allows for the absorption and release of more heat energy during the combustion process, contributing to the higher OPR (overall pressure ratio) values observed on the chamber wall [30].

Figure 19 suggests that the hydrocarbon fuel H_2 engine operates most economically within a certain range of Mach number. Outside this range, the engine efficiency drops, which leads to a decrease in OPR. On the other hand, OPR for hydrogen fuel shows a different trend. It shows a steady increase with increasing Mach number, without a noticeable decrease as observed in the case of hydrocarbon fuel. This behaviour indicates that the hydrogen fuel engine maintains its efficiency and performance over a wider range of Mach numbers compared to the hydrocarbon fuel engine.

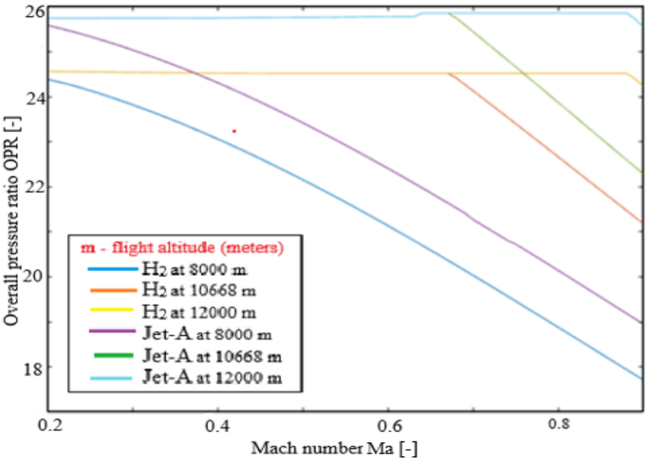

Fig. 19. Difference between hydrocarbon and hydrogen fuel depending on OPR coefficient value and Mach number [30]

Demonstrated Horus-Energia development technologies for hydrogen-powered gas engines at work [35]. They employ WUZG technology, which entails using a multi-point injection system with separate injectors for each cylinder located in the intake manifold close to the cylinder heads in place of a gas-air mixer at the engine's air intake. Any industrial gas engine can be equipped with the universal MUZG and WUZG systems, which increase the engine's flexibility and efficiency even when it runs on conventional fuels following installation. Improved knock combustion margin detection is the primary factor in improved performance, but ongoing engine condition monitoring and suggested corrective settings for the full process, from mixture creation to combustion. The Perkins test engine was used to test this. Methane and hydrogen in the proper ratios were used to power the device during the experiments. Each stream's gas flow was monitored independently and concurrently. To produce a fuel gas mixture with the necessary ratios and to modify it at the necessary speed, the amounts of hydrogen and natural gas were adjusted during mixing. A graph illustrating how engine efficiency varies with load for various fuels is displayed in Fig. 20. It is evident that a 50:50 hydrogen to methane mixture yields the maximum efficiency (over 40%) at 100% load. Pure methane feed results in the engine's lowest efficiency (for all efficiency scenarios). As a result, incorporating hydrogen into gas fuel enhances engine efficiency through improved combustion efficiency. Because of the extinguishing distance, zones with an extremely lean mixture, which is non-flammable for methane, are typically found near the cylinder walls, which further restricts the spread of flames in these areas. These areas cause "methane slip," or direct methane emissions from the exhaust system, which lowers engine efficiency. The situation improves when hydrogen is added to the fuel since it has a much shorter extinguishing distance and a much greater flammability limit. Less unburned fuel leaks out of the engine, and the number of non-flammable zones is far fewer.

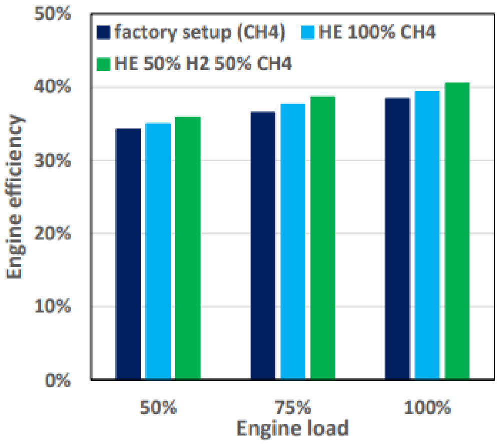

Fig. 20. Perkins engine efficiency depending on engine load [35]

Optimizing current gas turbine engines for hydrogen compatibility is essential to solving the issue of fossil fuel depletion. A new method was put out in this paper [26]: changing the amount of hydrogen present in various nozzle groups in gas turbine combustors. In comparison to the cases of homogeneous fuel of natural gas only and natural gas-hydrogen mixtures, the impact of inhomogeneity or variations in hydrogen concentration in the middle and outer nozzles on combustion dynamics and emissions was examined through experiments using a full-scale combustor of a commercial F-class gas turbine model. Cofiring hydrogen reduced CO_2 emissions but increased NO_x emissions. With a 41.2% increase noted for a 30% co-firing ratio, the peak amplitudes of the combustion dynamic pressure were linearly related to the co-firing ratio, particularly in the frequency range of 125–245 Hz. The findings showed a strong relationship between NO_x emissions and various degrees of heterogeneity as well as combustion stability. Furthermore, enhanced hydrogen co-combustion efficiency was noted under more heterogeneous conditions with intense hydrogen injection into the centre nozzle, which resulted in a 22% reduction in the peak amplitude of the co-combustion limiting frequency domain for a 25% co-combustion ratio [26]. The critical hydrogen co-firing factor may have expanded as a result. In order to improve combustion stability and for effective hydrogen co-firing, heterogeneous natural gas-hydrogen mixtures are a viable approach that could pave the way for cleaner energy production.

It was looked into how hydrogen co-combustion affected the emissions and performance of airplane engines. JetCat P140RXI engines and the DGEN 380 developed in the GSP (gas turbine simulation program) were studied using zero-dimensional models. The actual gas model and NASA Chemical Equilibrium Applications (CEA) equations serve as the foundation for the combustion computations in GSP. Engines running on Jet A-1 fuel and hydrogen or methane mixtures had their performance evaluated. For specific altitudes and flight speeds, the simulations were run first on the ground at the design position and then in flight. Due to hydrogen's and methane's higher calorific value, the thrust and temperature behind the turbine somewhat increase as the mixture's gas content rises, while the specific fuel consumption falls. For kerosene blends with hydrogen or methane, the JetCat and DGEN 380 engines' performance has been estimated. These engines will be converted to gaseous fuels using this expertise. The zero-dimensional combustion chamber model and the range of accessible chemicals are two of the GSP's fuel and emission constraints.

The performance of the JetCat and DGEN engines was also predicted using Generalized Spray Combustion (GSP) combustion modelling. DGEN and JetCat are powered by hydrogen or kerosene-methane mixes. Because hydrogen and methane have larger calorific values than other fuels, the temperature of the thrust and exhaust gases rises somewhat as the fuel's gas content increases, while the specific fuel consumption falls [28]. The results demonstrate the impact of hydrogen co-combustion on engine performance, which is crucial for conducting experiments and fuel system modification. In order to compare fuel usage under various scenarios, basic aircraft missions were modelled. However, compressor and turbine characterisation and model verification are necessary for simulating off-design operating circumstances. The combustion chamber must be divided into zones, and a multisector must be used for emission calculations.

In addition to allowing fuel mixture testing, the downsizing of turbine jet engines creates new opportunities for their application in smaller aircraft. In order to ascertain the station characteristics of the unit thrust and unit fuel consumption, measurements were made in the GTM 400 MOD engine. Polynomials that describe the changes in the range of applied rotational speeds were found for both parameters. Under the rector's grant, the work is the initial phase of the study. Its goal is to develop a hybrid turbojet engine that runs on hydrogen and aviation kerosene. The goal of the study is to examine the potential of using hydrogen in turbojet engines. One of the fuel additives that the European Union has authorized for use is hydrogen, which compels the aviation sector to lower its exhaust emissions into the atmosphere. In addition to improving aviation kerosene, hydrogen has the potential to be used as an alternative fuel.

The trend function for variations in thrust and specific fuel consumption, as well as specific fuel consumption as a function of rotational speed, was established based on the engine's experimental testing (Fig. 21).

The particular thrust rose by 77% as the rotating speed increased. Concurrently, there was a 75% drop in the specific fuel usage. The stand's developed features made it possible to ascertain the aircraft's operational parameters, which will be used to install the tested engine. These features also made it possible to calculate how utilizing admixtures or different fuels would affect thrust and fuel consumption.

Fig. 21. GTM400 MOD engine [6]

Preliminary findings from the creation of a fuel/air injector for the FT4000 gas turbine, which permits the use of hydrogen as an emission-free fuel for effective power generation, are presented in the paper [21]. Pratt & Whitney and RTX Technology Research Centre used key technology from the Pratt & Whitney PW4000 turbofan engine to produce the low NO_x combustor for the FT4000 engine. Through experimental evaluation of existing production equipment with increasing hydrogen content combined with natural gas, the study described here enhances the FT4000 combustor's technology readiness level for hydrogen operation. The dual-fuel nozzle can run the FT4000 combustor on 100% hydrogen with little nitrogen oxide (NO_x) emissions, according to high-pressure single-sector combustion bench testing that has been finished [21]. Opportunities to increase the fuel nozzle's durability under high hydrogen conditions are highlighted by metal temperature readings and video photos of the flame structure from zero to 100% hydrogen. In order to achieve low emissions and good thermal efficiency, the modern FT4000 production engine runs on fuel oil or natural gas with water injection. Mitsubishi Power Aero uses this engine, which produces 70 MW in wet compression operation with a simple cycle efficiency of more than 41%. According to the study's findings, FT4000 engines with dual fuel nozzles that are now in production can run at base load on hydrogen mixtures that contain water and natural gas [21].

The utilization of gaseous fuels, such as hydrogen, in engine operation enhances efficiency while significantly reducing harmful exhaust emissions. The study in [37] explores a two-stage passive hydrogen combustion system to examine knock combustion under different process conditions. Experiments were conducted using a single-cylinder AVL 5804 engine to evaluate the influence of the centre of combustion (CoC) and the excess air ratio (λ) on engine knock and other performance parameters. The tests were performed at a constant engine speed of 1500 rpm, with CoC adjustments ranging from 2 to 18°CA aTDC and λ values varying between 1.25 and 2.0. The findings indicate that for λ values between 1.25 and 1.5, knock combustion is relatively intense, requiring further increases in λ to mitigate it. Additionally, the excess air ratio (λ) was found to have a significantly greater impact on knock occurrence than the centre of combustion position [37]. Under the analysed conditions, a significant reduction is possible only by increasing the excess air ratio.

The crucial significance that material selection and design play in guaranteeing the safe and effective functioning of ammonia and hydrogen gas turbine engines was examined in this research [4]. Finding the right materials becomes crucial since these energy sources have special combustion properties in turbine combustion chambers. In order to identify improvement possibilities and identify flaws and degradation paths of turbine components, a thorough material characterization is necessary. High-pressure turbine blades, which are a crucial factor in determining service life, are particularly vulnerable to mechanical failures and thermal deterioration due to elevated turbine inlet temperatures. The difficulties in designing ammonia-hydrogen turbines are discussed in this paper, along with problems including stress corrosion cracking, hydrogen embrittlement, and ammonia corrosion. The essay highlights the interaction between technical advancements, equipment specifications, operating standards, and analysis methodologies and promotes the use of modern analytical techniques in both materials development and risk assessment to assure engine safety and efficiency.

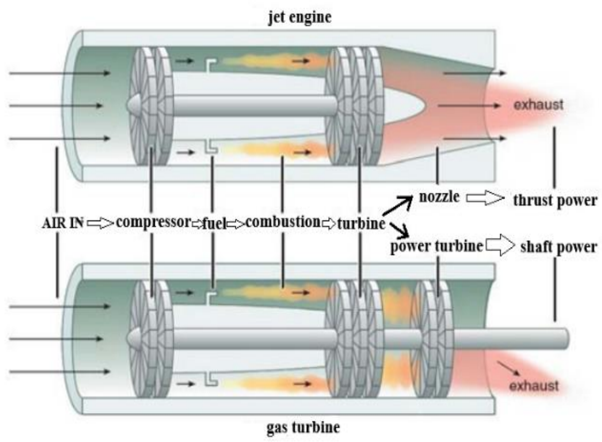

Fig. 22. The fundamental arrangement of a stationary gas turbine and jet engine [4]

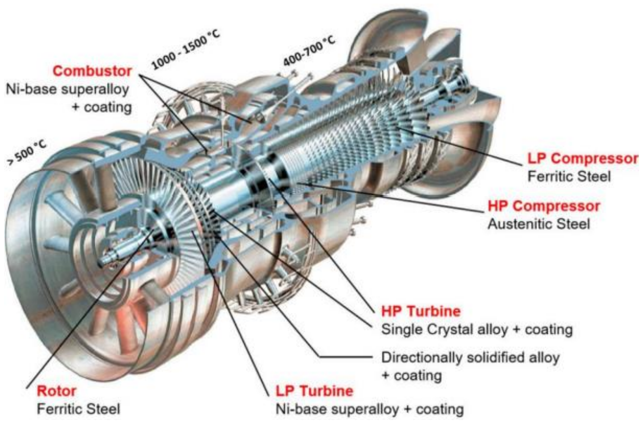

Fig. 23. The Alstom gas turbine's primary components, exposure circumstances, and materials utilized in various sections [4]

In a high-pressure turbine (Fig. 22), the spinning turbine blades face intense temperature and stress combinations post-combustion. These blades feature slim walls and a multi-layer design, allowing for intricate internal cooling systems. They are made of single-crystal nickel-based superalloys coated with a porous, low-conductive yttria-stabilized zirconia layer that serves as a thermal barrier. The blades are connected to turbine discs composed of polycrystalline nickel-based alloys. Engine discs, critical components for safety, are typically produced from powders that are consolidated and shaped through extrusion and superplastic forging to enhance strength and durability. Their inability can result in disastrous outcomes. Consequently, cutting-edge materials science and technology are employed to guarantee their optimal quality and performance. Polycrystalline cast nickel-based superalloys are prevalent in the rotating and stationary components of the turbine section's later stages. Engine shafts need to possess significant strength and fatigue resistance, typically crafted from high-strength steel or nickel-based superalloys.

It is clear from thermodynamics that factors like temperature and pressure have a big impact on the combustion cycle's efficiency and properties. Understanding how hydrogen affects flame temperature is crucial, particularly at high concentrations. A short-term approach that offers efficiency and maybe lowers emissions is to combine hydrogen and natural gas [4]. There are significant obstacles when using ammonia and hydrogen mixtures in gas turbines from a materials perspective. Problems like hydrogen embrittlement and ammonia-induced corrosion significantly impact the performance and lifespan of turbines.

Proposals for using fuel cells or hydrogen combustion to power turbine engines are also included in the article [22], along with a discussion of the fuel's economics. As a result, new aviation fuel types, combustion techniques, and combustion chamber models must be created. The potential applications of hydrogen propulsion in aviation are discussed in this article.

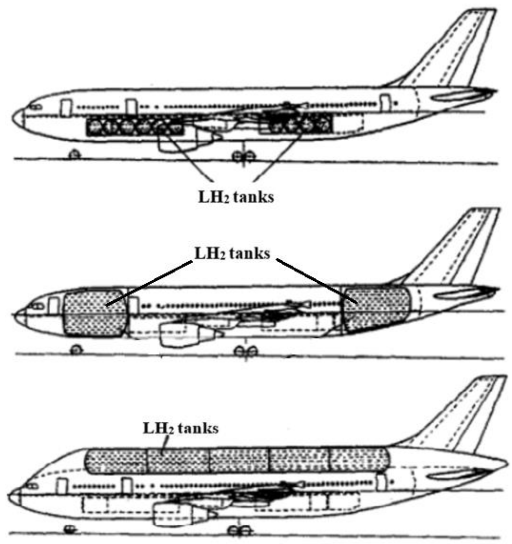

Fig. 24. Conceptual layout of fuel tanks in an aircraft [22]

Furthermore, the aircraft's hydrogen fuel tanks need more LH_2 than tanks for regular Jet A-1 fuel. The tanks should be positioned behind the passenger cabin due to the aircraft's balancing issue. The aircraft's centre of gravity would shift, though. Thus, putting two tanks – one in front of the cabin and the other behind it – or using the area above the passenger compartment for this purpose could be the second option. Figure 24 depicts an example of how liquid hydrogen tanks are arranged.

The analysis findings indicate that while hydrogen will totally eliminate carbon dioxide emissions, it won't totally eliminate nitrogen oxide emissions. As a portable source of clean energy, it is also a fierce rival to batteries. Efforts to overcome unfavourable chemical characteristics and infrastructure constraints are essential to the true future of hydrogen. Weight concerns are currently the most significant research challenges with the usage of hydrogen; tanks that are at least half as heavy must be developed. We might think that hydrogen has a future in aviation and belongs to liquid hydrogen because of the ongoing efforts and choices made by the biggest corporations in the world. Though the tanks will need to be larger due to its low density, the calorific value of this fuel argues in favour of hydrogen, and the mass of hydrogen needed for the mission will be nearly three times less than the bulk of aviation kerosene while retaining combustion efficiency [22].

The switch from current engines to pure hydrogen or hydrogen and natural gas combinations is crucial for gas turbine power systems, including hybrid fuel cell power plants. The potential for flashback zones, acoustic instability of combustion, elevated temperature of smoke tube walls, and occasionally elevated nitrogen oxide emissions are major issues, though. Burning pure hydrogen and natural gas-hydrogen mixtures can increase the efficiency of gas turbine power supply systems, according to this paper [33]. For the "Aquarius" type power plant, the arrangement of work operations in the pre-mixed combustion chamber and the combustion chamber with the sequential injection of energy and ecological steam is taken into consideration. The solution of the conservation and transfer equations in a multi-component reacting system serves as the foundation for the investigations of the fundamental aerodynamic and energy parameters of the gas turbine combustion chamber running on hydrogen-containing gases. In order to compute sensible parameters for ecologically friendly fuel combustion devices, a four-stage chemical method of hydrogen and natural gas mixed combustion is employed. Only when working with natural gas and hydrogen mixes that have a hydrogen component of no more than 20% (by volume) may a premixed combustion chamber be advised. Fuel combustion and the creation of flashback zones occur inside the swirler channels as the hydrogen content rises. Flashback zones don't happen in the combustion chamber of the combined cycle power plant "Vodoley" when it runs on pure hydrogen.

In the swirler channels and in the combustion chamber with supply of ecological and energetic streams (for the "Aquarius" type installation), Fig. 25 depicts the contours of the velocity values inside the combustion chamber during the initial formation of the hydrogen-air mixture.

The fuel enters the flow channel of these swirlers through several rows of tiny holes in the inner and outer blades of the pre-mixing chamber, where it mixes with air. This combination is delivered to the combustion chamber's primary zone, where gas recirculation ensures a consistent ignition.

We may deduce from the analysis of the data that the premixed combustion chamber system under consideration is only suitable for work involving natural gas-hydrogen mixtures, and that the mixture's hydrogen content should not be greater than 20% (by volume). Fuel combustion in the swirler channels and the emergence of flashback zones are caused by a rise in the hydrogen concentration in the mixture with natural gas [33].

a) b)

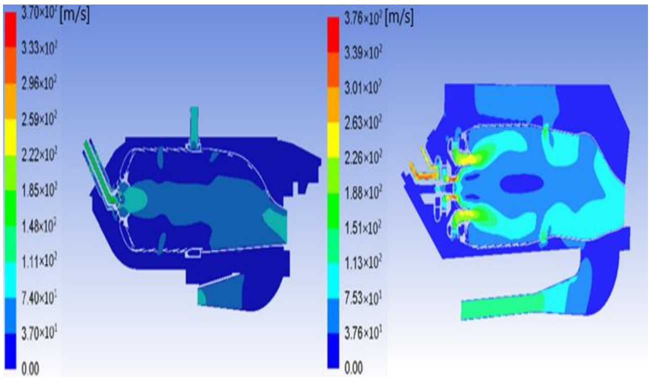

Fig. 25. Contours of the combustion chamber's velocity values [m/s] with steam injection (b) and component mixing beforehand (a) [33]

The paper [9] develops a mathematical model of the internal combustion engine's working process, which takes into account the addition of hydrogen to the fuel mixture, and creates a model for determining the parameters of a hybrid powertrain in the NEDC cycle modes. The results of the study showed that every 2% addition of hydrogen to petrol reduces the specific effective fuel consumption by 2.8–3.5%, depending on the speed mode. The study confirms the promising potential of using hydrogen as an additive to traditional fuels, which will help make them more environmentally friendly and improve transportation efficiency. This will also reduce CO_2 emissions and decarbonize the transportation sector. The computational methodology developed provides a solid basis for further research and implementation of innovative technologies in the area of hybrid propulsion systems.

Additionally, the sailing sector is working to lower greenhouse gas emissions and decarbonize. In order to compare the potential reduction of greenhouse gas emissions over the full life cycle of each fuel option with the Paris Agreement targets for international shipping, a novel approach was adopted in the article [40] wherein the greenhouse gas emissions associated with a year of global shipping fleet operations were used as a common unit of comparison. All greenhouse gases were evaluated over a 100-year time horizon (GWP100) using a life-cycle assessment from resource extraction to shipboard use. With potential emission reductions of 74–81%, 87%, and 85–94% when compared to heavy fuel oil, green hydrogen, biodiesel made from waste-derived biofuels, and bioethanol were shown to have the best decarbonization potential. However, several obstacles to the decarbonization of shipping have been discovered. Given the magnitude of the problem, ships driven by other fuels are too slow, and none of the alternative fuels under consideration are currently generated on a large enough scale to meet the energy demands of shipping. Additionally, it has been shown that the decarbonization potential of alternative fuels alone is insufficient, as no fuel option can meet the sector's requirement of 100% emissions reductions by 2050.

Additionally, the study identified a number of fuel choices' life cycle sensitivities that had not been given much consideration in earlier life cycle studies. This study includes both blue hydrogen (made from steam-methane reforming of methane from natural gas, with carbon capture and storage) and green hydrogen (generated mostly from water electrolysis using renewable energy). The primary drivers of interest in hydrogen as a fuel are its high energy density (120 MJ/kg), renewable nature, and non-toxic emissions during combustion (just water vapor). Proton electrolyte membranes (PEMs), which produce electricity to supply propulsion energy, are necessary for using hydrogen on board ships. The use of hydrogen in ships presents significant technological hurdles, including supply chain and bunkering infrastructure issues, health and safety concerns due to its explosive nature, and storage techniques (and the associated energy penalty). However, electrolyser costs are fast declining, and innovation is moving quickly [40].

According to Kanchirall's analysis on the usage of hydrogen fuel in shipping [18], roll-on/roll-off ships might reduce climate change by 85% when hydrogen is utilized in PEM fuel cells. Because blue-lane hydrogen production has received less attention in the literature, its ability to reduce emissions is less certain [40]. Although the precise percentage reduction was not given, the paper [1] concluded that blue hydrogen offered an overall reduction in emissions when compared to fossil fuels. The cleanest energy carrier is liquid hydrogen generated by solar electrolysis, according to the data (Fig. 26) (42.50 g CO_2 equivalent per MJ fuel). Additionally, liquid ammonia produced by solar electrolysis is cleaner than liquefied natural gas (60.76 g CO_2 equivalent per MJ fuel). On a full life-cycle basis, liquefied natural gas is still a cleaner alternative to methanol and dimethyl ether, even though the production of these products from biomass reduces overall greenhouse gas emissions significantly when compared to conventional methanol and dimethyl ether production from biomass. The total GHG emissions per unit mass (kg CO_2 equivalent per 1 kg fuel) from the manufacturing, transportation, and short-haul use of LNG, DME, and methanol are displayed in Fig. 26.

In conclusion, methanol has the lowest GHG emissions per unit mass, while LNG has the lowest emissions per unit energy when comparing the whole life cycle GHG emissions of DME and methanol.

A simplified chemical kinetics model for simulating the stand-alone combustion of syngas and NO_x production in a pilot-ignition dual-fuel engine, as well as the combined combustion of n-heptane and syngas, is included in article [34]. The combustion of syngas in a dual-fuel engine that uses a reduced injection of liquid n-heptane fuel with subsequent micro-pilot ignition was then predicted using this reduced mechanism in a thorough fluid dynamics simulation.

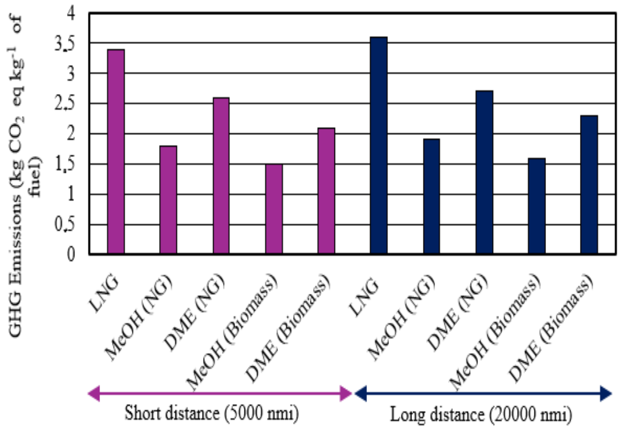

Fig. 26 Total greenhouse gas emissions per unit mass from the manufacture, usage, and transportation of methanol, DME, and LNG across short and long distances [1]

The prerequisites for n-heptane injection and syngas co-oxidation with n-heptane were precisely represented by the model. Additionally, it demonstrated a high degree of consistency with in-cylinder pressure and heat release rate (ROHR) experimental data. The study's findings highlight how well the simplified mechanism can replicate the burning of fuels based on syngas in an engine cylinder that contains up to 57% hydrogen. This reduced model is therefore ideal for replicating engine operating conditions using fuels supplied from syngas. All test settings showed strong agreement between the findings, which accurately reflected the effects of temperature, pressure, and equivalency factor on combustion characteristics. The experiment's notable sensitivity, particularly at high temperatures and pressures, is seen in Fig. 27.

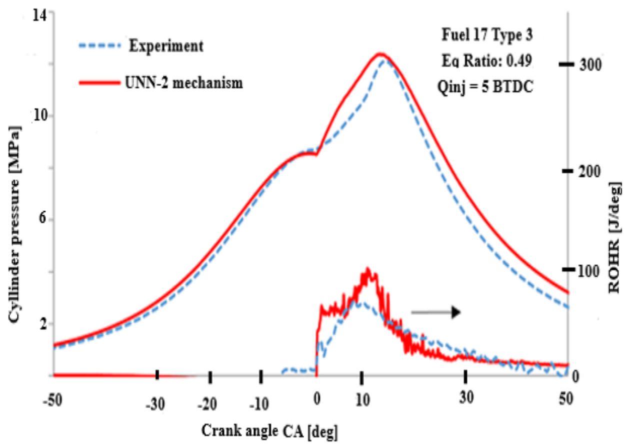

Fig. 27. calculated and experimental cylinder pressure and heat release rate curves for micro pilot initiated n-heptane syngas combustion in a dual fuel engine; air-fuel ratio – 0.31; injection timing – 13° [34]

More research is required to pinpoint the precise mechanisms causing this disparity and adjust the relevant constants in order to model hydrogen combustion in dual-fuel IC engine circumstances effectively. Since pure hydrogen and carbon-based fuels have very different oxidation and combustion properties, it was actually not initially anticipated that the UNN-2 mechanism would offer excellent accuracy for pure hydrogen mixes.

4. Conclusions

From the above, it can be concluded that multi-fuel turbine engines can significantly improve the energy efficiency and compliance with the most stringent exhaust emission standards of hybrid systems, offering new opportunities in the context of future mobility. In the context of research on new fuel technologies, multi-fuel engines can be tested for efficiency and combustion efficiency of different types of fuels, which can lead to innovations in the field of power supply. It is worth noting that the use of multi-fuel engines may require special design and technological solutions to enable efficient combustion of different substances, as well as maintaining the necessary performance parameters. Turbine engines offer numerous advantages, such as high efficiency, low exhaust emissions, and the ability to operate on different fuels, which makes them a versatile solution for many applications. However, the challenges related to production costs, maintenance, and efficiency in different operating conditions still require further research and technological development. A literature review was conducted using the available literature on the analysed topic. The results and their analysis led to the following conclusions:

1. In the context of research into new fuel technologies, multi-fuel engines can be tested for their performance and combustion efficiency of different fuel types, which can lead to innovations in the field of power supply.
2. It is worth noting that the use of multi-fuel engines may require special design and technological solutions to enable efficient combustion of various substances, as well as maintaining the necessary performance parameters.
3. Modelling the processes occurring in this type of engines will contribute to shortening the time of conducting these studies and, as a result, will accelerate work on the effectiveness of this type of approach to the multi-fuel problem.
4. Hydrogen as an alternative fuel will not completely eliminate nitrogen oxide emissions, but it will effectively reduce carbon oxide emissions. It also poses strong competition to battery power as a mobile carrier of clean energy. However, the future of hydrogen depends on overcoming the challenges related to infrastructure and its unfavourable chemical properties. Current research on the use of hydrogen focuses mainly on the problem of mass – it is necessary to develop tanks that will reduce it by at least half. Ongoing work and decisions made by the world's largest companies indicate that hydrogen has potential in aviation, especially in the form of liquid hydrogen, and in the automotive industry as a counterweight to battery-powered vehicles. Its high calorific value can be considered a significant advantage, but due to its low density, the tanks must be larger, although the mass of hydrogen needed for the mission will be almost three times smaller compared to the mass of aviation kerosene, while maintaining combustion efficiency.
5. Micro gas turbines are mostly tested in laboratory conditions, not in real operating conditions. Laboratory tests allow for controlling many variables and more precise monitoring of turbine performance parameters, which is more difficult to achieve in real conditions. However, conducting tests in real conditions, such as real load, changing weather conditions or specific local requirements, is essential for a full assessment of the performance, reliability, and long-term efficiency of micro gas turbines. The final implementation of these technologies therefore requires combining the results obtained in laboratories with tests carried out in real applications.

Acknowledgements

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Nomenclature

DME	dimethyl ether
GSP	generalized spray combustion
LNG	liquefied natural gas
OPR	overall pressure ratio
ROHR	rate of heat release
RCCI	reactivity controlled compression ignition
SAF	sustainable aviation fuel

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