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Alternative Fuels in Rail Transport and their Impact on Fire Hazard

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Abstract. The interest in alternative fuels results from the depletion of crude oil resources and, thus, the search for new energy sources. The article discusses alternative power sources introduced into the drive of rail vehicles. Their advantages and disadvantages are presented, especially the uncontrolled ignitions cases are described. Attention is drawn to the need to develop European regulations on the fire safety of rail vehicles using hydrogen cells, lithium batteries, or natural gas. Such requirements are particularly relevant for rolling stock passing through tunnels. They should include alternative propulsion vehicles and the transport of such loads (e.g. discharged lithium batteries).

Introduction

Most of the discoveries of oil deposits had taken place until the 1960s. In the following decades, discoveries were smaller and smaller despite technological progress and ongoing intensive searches carried out using the most modern technologies, including satellite research. Moreover, they are found in more and more inaccessible regions that require much more complex and costly mining and processing techniques. This is due to the higher oil density and the exploitation of deposits supersaturated with toxic hydrogen sulfide (e.g. Kashgan deposits), which require special precautions. Currently, oil consumption is greater than new discoveries, and the availability of its resources is estimated at 40 to 100 years [1, 20].

Considering the above and striving to reduce environmental pollution by gases and solid particles emitted in the combustion processes of hydrocarbon fuels, the search for alternative fuels to be used in various areas, including means of transport, has been undertaken. Within the meaning of the Directive [28], these include fuels that serve, at least in part, as a substitute for crude oil-based energy in transport and which have the potential to reduce the dependence of EU Member States on oil imports. An important argument is also the desire to decarbonize transport and improve the environmental performance of this sector. Alternative fuels include, among others: electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas (including biomethane) in the form of compressed natural gas CNG and liquefied natural gas LNG and liquefied gas LPG.

The search activities were enforced by legislative acts, including the European Green Deal approved by the European Commission on December 13, 2019 [29]. It assumes, among other things, reducing greenhouse gases in the transport industry by 95% by 2050.

Alternative Fuels in Rail Transport

In rail vehicles, the following are primarily intended for energy supply: electric batteries, natural gas, hydrogen, and hybrid supply.

Hydrogen. The prospect of using hydrogen as a fuel has a good chance due to its unlimited resources (it accounts for 94% of the universe [4]) and because it is considered the cleanest fuel from an ecological point of view (the effect of burning hydrogen is water vapor). A feature of hydrogen is its high diffusion coefficient of H_2 in the air. As a result, it easily creates a homogeneous combustible mixture. The wide yields of the mixture (0.14 – 9.9) allow the use of qualitative regulation in the engine by changing the mixture composition. Hydrogen is the lightest element in any aggregation state; it has the highest fuel heating value per mass (120 MJ/kg). Moreover, it is a very reactive fuel with a high octane number and combustion speed. Therefore, it is considered the fuel of the future. It is used in fuel cells. Their operation scheme was developed as early as 1838 by the German-Swiss chemist Christian Friedrich Schönbein. The cell consists of two electrodes – cathode and anode – separated by an electrolyte or an electrolytic membrane. Typically the electrodes are in the form of carburized platinum-coated paper as a reaction catalyst. After supplying hydrogen to the cell, it undergoes oxidation (gives away electrons), producing hydrogen cations. At the cathode, oxygen reacts with the electrons, reducing to oxygen anions. The membrane inside allows protons to flow from the anode to the cathode while blocking other ions, including the formed oxygen anions. Upon reaching the cathode, the hydrogen cations react with these oxide anions to give water, and the electrons from the anode reach the cathode via an electrical circuit, producing energy. However, the breakthrough in the use of hydrogen cells did not come until the 1960s, when they became part of NASA spacecraft.

Hydrogen, unfortunately, also has its disadvantages. It is a colorless and odorless flammable gas that can form explosive mixtures with air. The following basic parameters describing the combustible and explosive properties of hydrogen include:
– explosion limits in the air: 4.1-74.2% vol.,
– limits of detonation in the air: 15-63.5% vol.,
– maximum pressure increase during an explosion in a mixture with air: 625 kPa,
– auto-ignition temperature: 580 ° C,
– minimum ignition energy: 0.011–0.02 mJ.

Hydrogen belongs to the T1 temperature class and the IIC explosion group. The above means that this gas has a relatively low lower explosive limit and can burn in the air over a very wide concentration range. Little energy is required to initiate combustion. The safety data sheet for hydrogen describes it as an extremely flammable gas and gives the following precautions: keep it away from heat sources (heating a pressurized container above 50 ° C may cause it to explode). It is also essential for safety that the flame of hydrogen burning in the air at atmospheric pressure is invisible. Moreover, hydrogen is characterized by a relatively low inversion temperature (about 205 K), which means that during a gas expansion (e.g. when flowing out of a leak), the temperature of the flowing gas stream increases (due to the negative Joule-Thompson effect) [2].

Safe use (including storage) of hydrogen requires knowledge of its specific properties and the effect of cryogenic temperatures on the material's behavior. Structural steels from which tanks and fasteners are made may undergo hydrogen corrosion in an environment containing hydrogen (low-temperature – below 100 ° C and high-temperature – above 200 ° C, steel decarburization, HTHA – High-temperature hydrogen attack), which results in a significant reduction in the mechanical properties of steel, in particular a decrease in strength, an increase in plasticity and creep rate, and leads to the formation of microcracks [2, 12]. Hydrogen also has a negative effect on non-metallic materials (elastomers for valve seats, seals), and their use should be verified by reliable test results confirming the ability to maintain the required physicochemical characteristics of the selected material under the expected conditions of contact with hydrogen. Welds are also

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prone to hydrogen embrittlement in any hydrogen environment. In the heat-affected zone, the so-called "Hard spots", residual stresses and microstructures contributing to brittleness, often arise. Post-weld annealing may be required to restore the structure. When building an installation for contact with hydrogen, the requirements for welding metals [12] should be met (e.g. ASME B31.12-2014 [36]. As demonstrated by the tests and numerical simulations carried out in SNL [11], hydrogen leakage from the tank may cause combustion deflagration and even detonation in the tunnel.

The significant disadvantages of hydrogen cells are still high production costs (cheaper methods force the combustion of fossil fuels, which is not indifferent to the environment).

Rail Vehicles with Hydrogen-Powered Drive. The term "hydrail" was first used on August 22, 2003, during a presentation at the Volpe Transportation Systems Center of the US Department of Transportation in Cambridge. Potential applications for hydrogen-powered railways include all types of rail transport: suburban, long-distance, high-speed, freight, mine, factory, and special vehicles in parks and museums. [14].

The first fuel cell train to be introduced into public transport was the Coradia iLint multiple unit manufactured by Alstom in Salzgitter. From September 17, 2018, operates a route of approximately 100 km from Cuxhaven to Buxtehude in Lower Saxony (Germany). It should be noted that the critical elements of the drive system, in addition to the set of fuel cells, also include the lithium-ion battery system, as well as an external converter, hydrogen tank, traction inverter, and traction motor [1, 3].

The Polish company PESA from Bydgoszcz also designed the SM42Dn hydrogen-powered locomotive. It includes four asynchronous electric motors with a total power of 720 kW, LTO (lithium titanate) battery with a capacity of 167.7 kWh, and ABB traction inverters with an auxiliary converter 3 x 400 V. The hydrogen fuel in the PESA SM42Dn locomotive will be stored in tanks under the pressure of 350 bar. The power sources will be 2 Ballard fuel cells produced in Canada with a total power of 170 kW [15].

In January 2021, the European FCH2RAIL Project was launched with partners from Belgium, Germany, Spain, and Portugal. Their task is to develop a new zero-emission train prototype. The vehicle is to be equipped with a hybrid and modular drive system that combines electric power from the overhead contact line with fuel cell power. The latter part will consist of hydrogen fuel cells and batteries. They must be connected and controlled so that the system meets all requirements and is cost-effective. [13].

Lithium Batteries. At the beginning of the 20th century, the great potential of lithium as a battery material was noticed. It is a metal with the lowest density, high electrochemical potential, and a high energy-to-mass ratio. The American chemical physicist George Newton Lewis began early experiments with lithium batteries in 1912. However, it was not until the 1970s when research (undertaken by John Goodenough, Stanley Whittingham, and Akira Yoshino) led to the development of lithium-ion batteries (for which they received the Nobel Prize in Chemistry). Exxon launched the first lithium-based battery in 1978. However, only after Sony produced a series of lithium-ion batteries in 1991 became it commonplace [21, 22].

A lithium-ion (Li-Ion) battery consists of a positively charged graphite cathode and a negatively charged lithium anode. The other two parts contain an electrolyte and a separator between the two charged electrodes. During charging, the lithium ions move from the carbon anode to the cathode made of lithium oxide and another metal and are stored there. This technology allows you to accumulate twice as much energy as in nickel-metal hydride (NiMH) batteries of the same weight and size. Because lithium-ion batteries are one of the lightest, their use began with all kinds of electronic equipment. However, there has also been growing interest in using large lithium-ion battery packs (typically 20 to 100 kWh) in electric automotive vehicles in recent years. At the same time, car batteries differ significantly from those used in electronic equipment. The differences result mainly from the more significant requirements related to working conditions and the more excellent required durability, reaching ten years. Moreover, the packages are equipped with special cooling and heating systems, ensuring optimal operating temperature [21-23].

The next step in developing lithium batteries was the development of lithium titanate Li4Ti5O12 batteries (LTO). By working on this technology, manufacturers obtained a somewhat developed nanocrystalline anode structure, which became the main advantage of the products. Unlike the porous carbon used to create other types of lithium batteries, the nanocrystalline structure makes the large anode surface "usable" ensuring surface stability. The LTO technology enables an effective anode area of approximately 100 m^2/g, while for carbon anodes, only about 3 m^2/g. Due to the large anode area, the charge is transferred much faster, and the characteristics of permissible currents are higher. All this ensures the device's operating time, stability, and safety of use [18].

The advantages of lithium batteries compared to other types of batteries (e.g. NiCd and NiMH) include 3 times greater capacity with the same battery size and lower weight, many times greater energy density, no memory effect, no heavy metals in the composition (harmful to the environment), a high operating temperature range (even from -20 ° C to 50 ° C) as well as a longer service life [23].

Li-ion batteries also have disadvantages. Dangerous incidents related to their use can still be heard about. In most cases, a fire and an explosion occurred due to a short circuit between the anode and the cathode due to overheating of the cells, e.g. a fire from spilled fuel or overheating due to improper charging or overcharging. The result is a rapidly progressing chain reaction, often out of control. The temperature rises quickly, and the separator between the electrodes melts, which fuels the further heating of the battery. The loss of control over the system temperature increases causes the so-called thermal runaway (Fig.1).

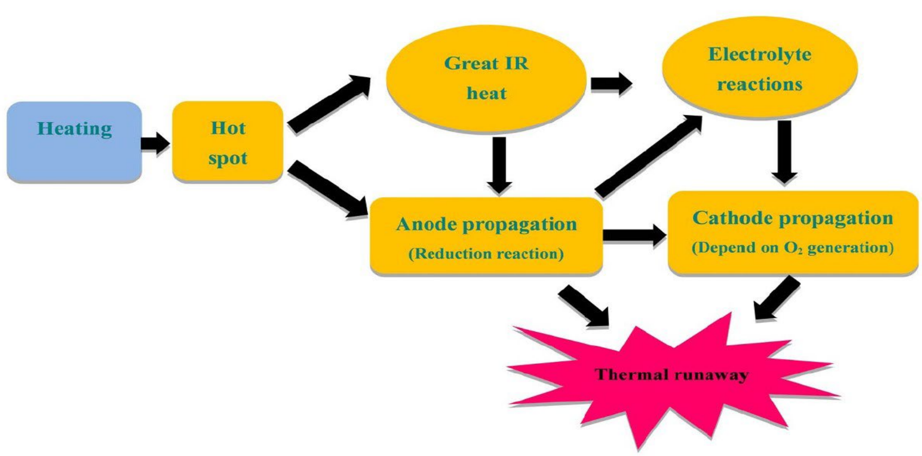

Fig.1 Mechanism of runaway in a lithium-ion battery under heating conditions [5]

The above causes a chain reaction, especially danger in batteries consisting of many cells because it initiates the reaction in subsequent, often undamaged, cells. As the temperature rises, the cathode emits oxygen which reacts with the organic electrolyte, eventually causing the battery to ignite or explode.

There are also battery design errors, among other non-mechanical causes of Li-ion battery fires. High-profile cases include explosions of batteries in telephones onboard airplanes, an explosion of an electric bicycle battery, or an outbreak of a battery in a Tesla car (which resulted in the death of the driver), where six days after the accident, there was a spontaneous explosion and another fire of the wreckage towed to the parking lot [16, 17]. While the largest fire in rail transport occurred on April 23, 2017, in the Union Pacific train, in which the container caught fire while carrying discharged lithium batteries to be recycled [19]. Although a long time has passed since these events, battery systems containing lithium-ion cells still pose a challenge in terms of fire safety. Extinguishing such fires is still a problem for emergency services. Research conducted by the Federal Aviation Administration (FAA) in the USA showed that water-based fire-fighting materials proved to be the most effective. Effective actions were based on the combination of the effect of extinguishing the burning electrolyte and the simultaneous cooling of the cell, so the role of as much water as possible as a cooling factor turned out to be very important: the more water, the better. Gas-based refrigerants showed good ability to extinguish the burning electrolyte but did not provide adequate ability to cool the cell. Therefore there is a risk (as in the case of the Tesla accident mentioned above) that another spontaneous fire may occur even many hours after the first fire is extinguished.

Natural Gas. It is often called the blue fuel and even the fuel of the 21st century. Its composition may change because it is influenced by the place where the deposits are exploited. However, the main component of natural gas is always methane. In addition, natural gas may contain various amounts of such gases as ethane, propane, butane, nitrogen, and organic and mineral compounds. In addition, noble gases (helium, argon) also appear there. Natural gas has no smell whatsoever. It is specially odorized to make it easier to smell when leaking.

Natural gas is used to power vehicles in compressed (CNG) or liquefied (LNG) form. This fuel has several advantages over other propulsion methods, including high calorific value and low exhaust emissions: reducing CO_2 emissions by 10% and particulate matter (soot) by 100%. Therefore, it has also been used in rail vehicles. For example, it is intended for use in the following vehicles:
- freight locomotive on the route Jacksonville - Miami (Florida, USA) [24],
- new railbuses in the Czech Giant Mountains on the Martinice v Krkonoších railway line from Rokytnice to Jizerou, in 2022 [25],
- a railbus used to transport tourists in the Rimini area (Italy) [26],
- Renfe trains (Spain) under the EU-funded RaiLNG program [27].

Fire Safety of Rail Vehicles with Alternative Drive

Passenger rail vehicles running on an interoperable TEN have to comply with the requirements of the LOC & PAS TSI [30]. On the other hand, the freight rolling stock is covered by the requirements of TSI WAG [31]. In addition, the SRT TSI [32] applies to rolling stock running in tunnels. In these specifications, the requirements of the EN 45545 series of standards (Part 1 to 7) [36] are referred to, depending on the area, in the scope of fire safety. The general purpose of these standards is to ensure the safety of passengers and train crew. The series of standards includes fire protection measures and requirements aimed at minimizing the likelihood of a fire occurring and controlling the speed and extent of fire spread, i.e., as a result: minimizing the impact of the products of a possible fire on passengers and crew. Part 7 specifies the requirements for flammable liquids and liquefied hydrocarbon gas installations, e.g. traction, auxiliary power units, heating or cooking, necessary to meet the purposes defined in Part 1. Its general requirements apply to tanks, piping, flexible connections, distribution system, ventilation devices, internal combustion engines, and heating devices. The requirements of EN 50153 [38] for containers and piping, EN 10204 [39] for each metal used in liquid or flammable gas installations, and EN 15227 [40] for LPG cylinders are also referenced. However, this standard does not cover the installation of alternative drives and does not contain any special requirements dedicated to these installations. This is because these systems started to be implemented in rail transport after the establishment of EN45545 [36]. Therefore, it seems necessary to analyze the current provisions concerning alternative drive installation elements and supplement them with requirements adequate to the above-described characteristic properties of individual fuels. The above applies, for example, to the requirements for hydrogen installations to prevent uncontrolled leaks. They should also be secured against a possible hazardous event, such as derailment, collision, or spreading of a fire in another train area. These events can cause damage to alternate propulsion components, which can lead to an explosion with potentially catastrophic consequences.

It is considered advisable to adapt the requirements for hydrogen-powered road vehicles, including Regulation of the European Parliament and Council (1243 of 2019) [33], and Regulation No. 134 (UNECE) [34]. However, due to the use of hybrid drives in rail vehicles, the approval procedures should also include tests and requirements for lithium batteries.

Incidents of spontaneous combustion and explosions of lithium batteries have prompted various laboratories to undertake tests to identify the magnitude of their fire hazard. These tests were carried out for batteries of multiple sizes with different charge levels and with the use of various methods and test stands (furniture calorimeter [5], Tewarson apparatus, CDG calorimeter [6], adapted decompression chamber [8], Single Burning Item (SBI) apparatus [7].

All tests confirmed that the more charged the battery, the faster ignition from the initiated source. The HRR value increases with the battery charge (for example, from 13 to 57 kW for a battery with an energy capacity of about 100 Wh [7]). In addition, these tests revealed the emission of toxic compounds (SO_2, HF, other - depending on the electrolyte composition of the batteries) that pose a risk to humans in the event of ignition in a closed/confined space. The above demonstrates the need to consider the specific requirements for passenger composite vehicles powered by lithium batteries and locomotives powered by lithium batteries (or carrying a battery load in a train) passing through tunnels. These studies allow for a more comprehensive understanding of phenomena occurring in uncontrolled situations using lithium batteries. However, it seems necessary to introduce a unified test and approval method for rail vehicles. The procedure according to R100.02 regarding the rechargeable energy storage system (REESS) [35] is considered the most adequate. At the same time, the tests carried out at the CTO showed the need to verify it to obtain the repeatability of the method (clarifying the size of the ignition source and environmental conditions). The above is necessary when using it in type approval tests [9].

In the area of natural gas supply, there are also no European regulations dedicated to this type of fuel on the fire safety of rail vehicles. In this case, it is considered advisable to adopt the following documents ISO 12991: 2012 [41], NFPA 52 [42], and NFPA 59A [43].

Summary

The increasing use of alternative fuels for propulsion has a great chance of expansion due to more and more innovative technologies. The introduction of new power supply solutions gives the undeniable benefits of environmental protection. However, it entails the need to develop European regulations regarding the fire safety of rail vehicles using hydrogen cells, lithium batteries, or natural gas. Such requirements are essential for rolling stock passing through tunnels and should also apply to the carriage of this type of load.

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