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Operational experience and new developments for industrial gas engines fuelled with hydrogen fuels

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Since 2012 Horus-Energia has been developing the technology for the hydrogen fuelled industrial gas engines. The first three units were commissioned in 2014 and, in 2019, reached the forty thousand running hours milestone. The success of the first hydrogen project encouraged Horus-Energia to focus on further developments and improvements of the technology. Several R&D projects have been carried out since 2016 and resulted in two granted patents, and another one is currently being processed. The recent development project focused on hydrogen-hydrocarbon blends is in its final stage. The technology being developed creates a solid base for many new solutions that will cover a wide range of fuels and applications. The paper reports the experience from 40,000 hours of operation of hydrogen-fuelled industrial gas engines and presents the developments carried out by Horus-Energia with its research partners as well as the future development paths for the technology.

Key words: *hydrogen, industrial gas engines, cogeneration, on-site power generation*

1. Introduction

For many decades hydrogen was considered as a fuel of far-future solutions and labelled as too expensive and dangerous for daily use. Even though a lot of research projects were carried out on technologies for safe storage and use, as well as less expensive production, it still remained linked solely to the space industry.

The situation has changed recently, and hydrogen has suddenly become a fuel considered to be within reach for everybody. This, together with more and more hydrogen solutions for daily use already available on the market, is boosting current activities on further developments. Currently, there are available for regular sales: hydrogen fuelled cars, trucks, and buses; hydrogen fuel cells for household power generation; electrolyzers; hydrogen tanks for a wide range of storage pressures and more. Each significant industrial gas engine maker announces developments of its own products to allow the usage of hydrogen as a fuel, at least to some extent. However, most of the technologies presented nowadays are at a very early stage of development, usually at factory tests and improvements. Nevertheless, some OEMs put first prototypes into the initial phase of field testing [1, 7, 8, 10, 13]. Still, most companies working as system integrators do not have either a budget, capabilities, competencies, or facilities to develop engine technology, and thus, they are usually dependent on the technology available from industrial engine manufacturers.

The paper describes over a decade of Horus-Energia experience in development of technologies for industrial gas engines enabling hydrogen usage as a fuel for on-site power generation. The engines were modified inhouse by Horus-Energia and adopted to operate on gas fuels containing hydrogen at various proportions and even for pure hydrogen. Systems were installed on several applications, and the experience from tens of thousands of hours of operation in real conditions will also be present together with the next steps planned for the technology improvements.

2. Solution for low hydrogen content in gas fuel

The basic hydrogen technology available from Horus-Energia is based on the innovative and patented gas-air mixer system called the MUZG. Gas-air mixers are the most common solutions for industrial gas engines on the market due to their simplicity and high reliability, but they have a lot of limitations like slow response to changes in fuel properties, lack of capability to change gas-air mixture composition on demand, or operating range for air/fuel ratio. The MUZG technology, developed together by Horus-Energia and Cracow University of Technology, is much more advanced and sophisticated than typical mixer solutions. In the MUZG system, the gas dosing is additionally regulated by a fast reacting control unit [4, 5, 9, 11]. The MUZG system uses many additional sensors to monitor combustion process inside cylinders, to detect abnormal situations, like knock or misfiring, and to implement necessary correction for engine controls or to mixture composition. Thanks to fast algorithms and fast-response controllers the MUZG system can implement corrective actions within a single engine cycle.

This improves mixer operational flexibility and helps to overcome the main disadvantages of typical mixers i.e. narrow operating window for gas fuel calorific value and slow response when gas fuel calorific value changes – the gas fuel calorific value change causes change in stochiometric gas-air ratio and thus requires correction in stochiometric coefficient (lambda). Additionally, extended sensors and fast processing help to detect many abnormalities at their initial phase, which is very important to implement active knock protection. The operation near the knock limit enables high efficiency, but standard control systems of industrial gas engines create too high a risk of knock. Only effective early knock detection and fast response of the control system allow such engine operation.

The MUZG system was tested in 2017 and 2018 at Horus-Energia premised within R&D project co-financed by the National Centre for Research and Development. During tests, various gas fuels were specially composed to define the real operational limitations of the MUZG system. The tests were focused on wide range of fuel calorific value change, the methane number change and on maximum accepted change rate of these.

The main advantages of the MUZG system over typical mixers are shown in Fig. 1–3.

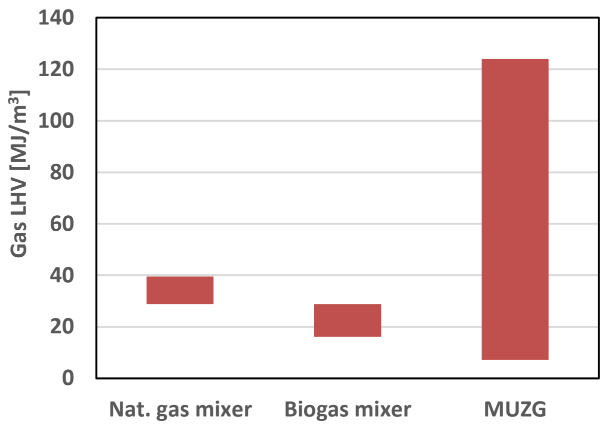

Fig. 1. Comparison of gas-air mixers operation window for gas fuel calorific value

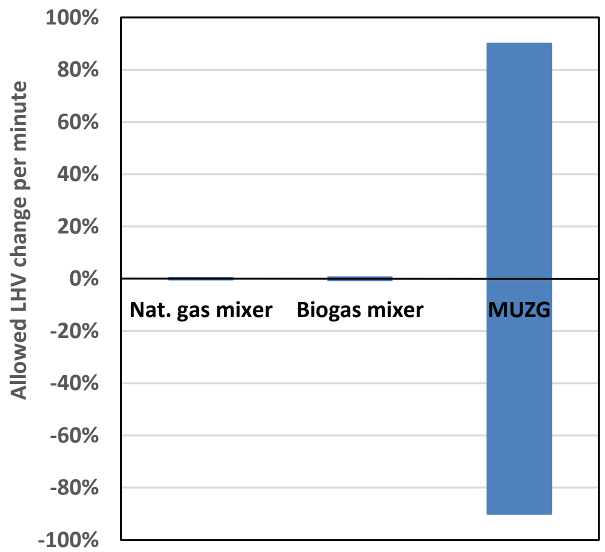

Fig. 2. Comparison of acceptable gas fuel calorific value change speed for stable gas-air mixer operation

The MUZG system tests showed its superiority over standard systems dedicated to industrial. The system allows a significantly wider operating window for gas fuel calorific value change. What is most important, the MUZG system does not require any additional inputs or settings when gas fuel calorific value changes. On the contrary, standard control systems need presetting for particular fuel and quite narrow operating window is than anchored with these initial values giving as a result much narrower operating range in reality than it seems from the theoretical range.

The MUZG system also has unique and incomparable capability in responsiveness to gas fuel properties change. As the tests showed, the MUZG system reaction time is over 100 times shorter than standard systems offer [4, 5].

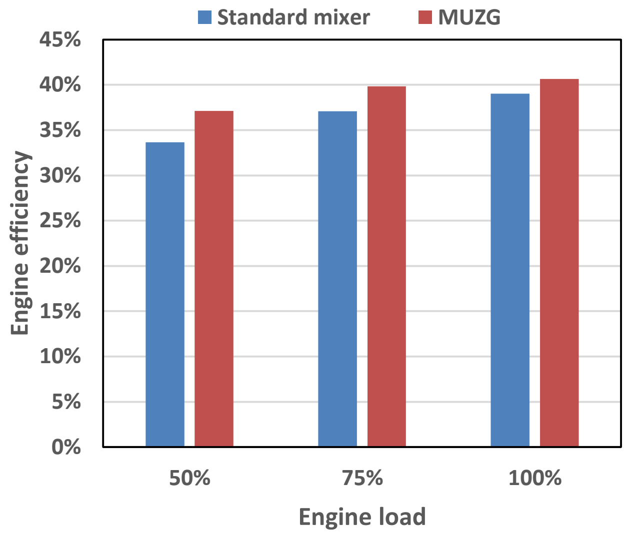

Fig. 3. Comparison of MAN E2876 LE302 gas engine efficiency for various gas-air mixers during operation on methane

The above mentioned advantages are very important when it comes to non-conventional gas fuels but the MUZG system provides significant benefits also for engines fuelled with conventional gas fuels. The visible efficiency improvement achieved during operation on methane results from more accurate fuel dosing linked to measured knock margin and fast processing of controls.

It is important to note that the MUZG system has been designed independently from the engine platform, so it can be installed on any industrial gas engine and will provide extremely flexible, self-adjusting, fast reacting, and efficiently optimized operation of the engine. Horus-Energia has successfully installed the MUZG on many gas engines, like MAN, Perkins or Rolls-Royce MTU.

3. Solution for high hydrogen content in gas fuel

The gas-air mixer solution, where fuel is delivered at the engine air inlet, fills quite a large volume with a flammable mixture and starts to be problematic and hazardous when hydrogen is the dominating gas fuel component. For such cases, the WUZG technology available from Horus-Energia is recommended. The WUZG uses the same control philosophy as the MUZG system, and the main difference is that instead of a gas-air mixer located at the engine air inlet, there is a multipoint injection system with individual injectors for each cylinder located in the intake manifold close to cylinder heads.

The WUZG system was developed in close cooperation between Horus-Energia and Cracow University of Technology already in 2013, and it has the same basic advantages as the MUZG system, but it offers an even faster response when the gas-air mixture composition change is required and enables the possibility to control each cylinder separately [2].

The exact hydrogen content in gas fuel when the WUZG system shall be used instead of the MUZG system is not defined and actually it comes more to gas fuel properties than only hydrogen content in it. Usually fuels with hydrogen content lower than 50% contain significant content of carbon monoxide, nitrogen and also carbon dioxide. Additionally, usually they are some process by-streams or by-products and they are available at low overpressure, typically some millibars, and are seldom cleaned. For such fuels it is more feasible to use the MUZG system. When fuel is clean and hydrogen content is over 50–60% the WUZG system is better and safer solution.

Like the MUZG system, also the WUZG system was developed independently from engine platform, so it can also be installed on any industrial gas engine. Horus-Energia has successfully installed such system on several Perkins (Fig. 4) and MAN engines so far.

Fig. 4. The cogeneration unit with Perkins 4016-61TRS2 industrial gas engine equipped with the WUZG system at customer site in Gaj Oławski

4. Solution for hydrogen-hydrocarbons blend

In 2022, another R&D project started and the aim was to develop a system especially dedicated to gas fuel that is a blend of hydrogen and methane (natural gas). It is meant to be used with future pipeline gas when (probably) hydrogen generated from renewable sources will be injected into the national gas grid and locally its level can change from nearly 0% to even 100% within a short period of time. The methane-hydrogen fuelled industrial gas engines are supposed to be installed in the cogeneration solutions operated locally in a distributed power generation system. For such operation it is crucial to ensure that hydrogen change in the entire range can be done when the engine is operating and without any required change in the engine load during the change. Also, the engine needs to accept quick changes of hydrogen content within the entire range regardless if hydrogen content is being increased or decreased.

The newly developed system is based on the features of the MUZG and the WUZG systems and it benefits from both systems advantages. For the project purpose, the Perkins 4016-61TRS2 industrial gas engine was modified in the autumn of 2022 (Fig. 5), but the system is independent from the engine platform and, as the previously mentioned ones, it also can be used on various industrial gas engines.

The genset was equipped with a heat recovery system providing nominal power of 1 MW electric plus 1 MW thermal power, and the cogeneration unit was tested in 2023 at Horus-Energia premisses (Fig. 6) with the very extended functional and operational test program. During the tests, the unit was fuelled with methane blended with hydrogen in the required proportions.

The test facility at Horus-Energia is equipped with a gas mixing station which allows online blending of fuel gas from its components – in this case, hydrogen was blended with natural gas from the gas distribution network. Hydrogen was delivered in a trailer at a pressure of 200 bar, reduced at the pressure reduction station to a level equal to natural gas pressure. The gas flow was measured simultaneously for each stream separately. During blending, the proportions of natural gas and hydrogen were changed to create the fuel gas blend with the required proportions and also to change them with the required rate. The tests covered the steady-state operation for the efficiency measurements (Fig. 6) and the dynamic tests for fast change of hydrogen content in the fuel at constant load (Fig. 7).

Fig. 5. The Perkins 4016-61TRS2 industrial gas engine is equipped with the specially developed system hydrogen-methane fuel system. The genset arrangement at Horus-Energia test facility

Fig. 6. The containerised cogeneration unit with the Perkins 4016-61TRS2 industrial gas engine at Horus-Energia industrial engines test facility

The functional test showed that the control system developed in the project provides better control and balance for the industrial gas engine than the original control system. Additionally, the addition of hydrogen in the fuel gas improves combustion efficiency and, thus, engine efficiency. The zones with the extremally lean mixture that is non-flammable for methane are usually located close to cylinder walls, which additionally limits flame propagation in these zones due to quenching distance. These zones are sources of methane direct emissions from the exhaust, known as methane slip, and this reduces engine efficiency. When hydrogen is added to the fuel, the situation improves, as hydrogen has much wider flammability limits and a much shorter quenching distance. The non-flammable zones are much smaller, and less unburned fuel is exhausted from the engine.

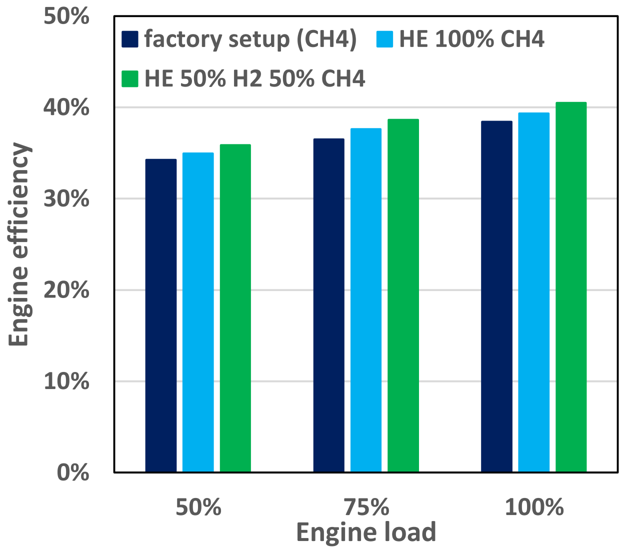

Fig. 7. The efficiency of Perkins 4016-61TRS2 gas engine with standard control system and with the developed one

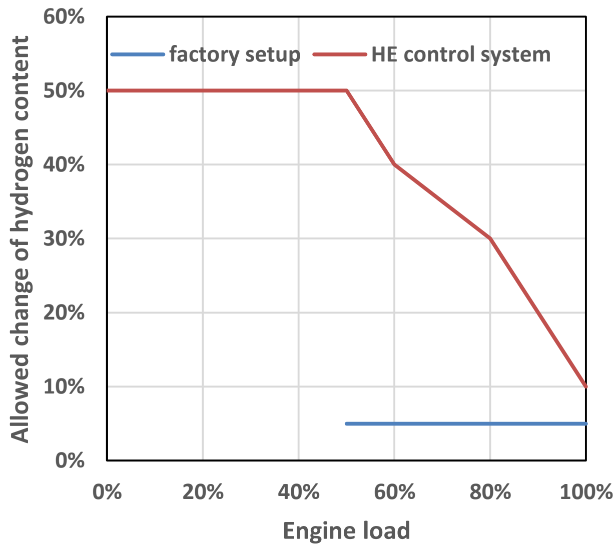

Fig. 8. The maximum allowed sudden change of hydrogen content for Perkins 4016-61TRS2 gas engine with standard control system and with the developed one

The dynamic tests showed that the implemented control system if compared with the standard control system, allows for a much wider range of hydrogen content in the fuel and a much faster change of hydrogen content. It is important to highlight that the engine with its original configuration has two limitations: hydrogen content cannot be higher than 5% (by volume), and the engine shall not be operated for a long time with loads below 50% of the nominal load. The new control system offers better dynamics because of its advanced control philosophy, which includes many more sensors and transducers and a fast data processing controller, which allows to detect even small change in the combustion process, evaluate the cause and react correctively from cycle to cycle. Thanks to such control system ability, the engine operation can be set for more efficiency optimal points but still with a safe distance from the knock margin, especially during fast changes of fuel properties or during fast loading or unloading. Additionally, when a fuel gas injection system is used, the system allows individual control for each cylinder with individually set mixture composition (especially individually set stoichiometric coefficient) and individually set ignition timing.

The observations for tests with hydrogen content over 50% are that further increase of hydrogen in the fuel blend has less influence on the engine efficiency, as the combustion process in the very lean areas is already well stabilised with 50% hydrogen in the fuel blend. Also, charge exchange is already well controlled as the system switches from mixer to injectors, so cylinders are flashed with pure air instead of mixture. Another observation is that due to a lean mixture and lower combustion temperatures NO_x emissions are lower when the share of hydrogen increases (Fig. 9 and Fig. 10).

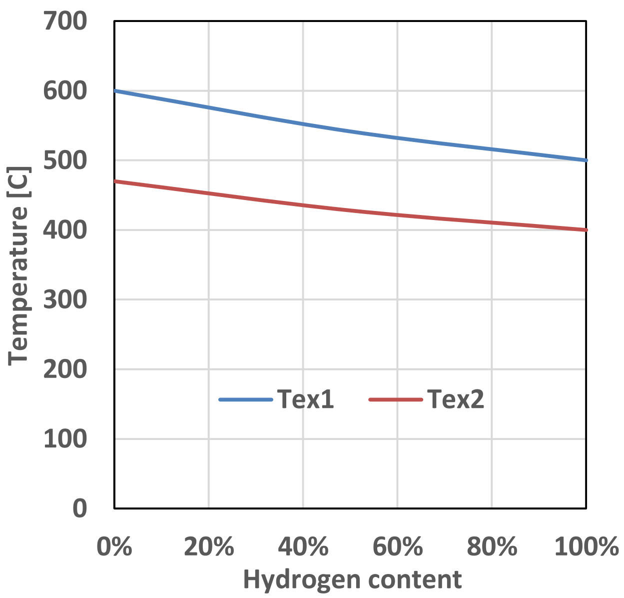

Fig. 9. The exhaust temperatures before turbocharger (Tex1) and after turbocharger (Tex2) for the Perkins 4016-61TRS2 gas engine fuelled with various hydrogen content in the gas fuel

It is important to note that the Perkins 4016-61TRS2 running at a nominal load of 1000 kW consumes about 90 kg of pure hydrogen per hour. Typical hydrogen trailer, as those used during tests at Horus-Energia premisses, contain about 320–400 kg of hydrogen, so one trailer is sufficient for 3.5–4.5 hours of operation only, not enough even to complete one full day of the tests. For that reason, further extensive performance tests are scheduled for 2024 and will be carried out at the location where hydrogen is available locally to avoid frequent hydrogen deliveries and related logistics.

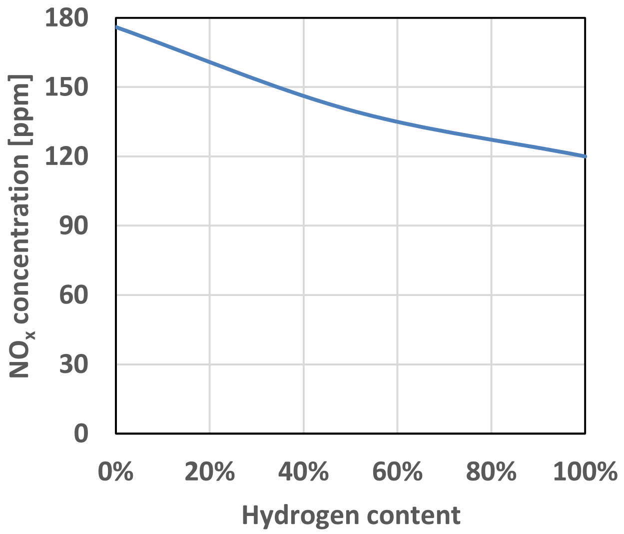

Fig. 10. The NO_x emission from the Perkins 4016-61TRS2 gas engine fuelled with various hydrogen content in the gas fuel

The last part of the test program will be the two years long durability test during normal operation of the cogeneration unit at selected customer.

The final version of the system will enable fuelling the industrial gas engine with a blend of hydrogen and gaseous hydrocarbons at any proportions with the same functionalities as the tested system.

5. Operational experience of the MUZG and WUZG systems

The very first WUZG system was commercially installed on three cogeneration units with MAN industrial gas engines commissioned in 2014 – one MAN E2876 LE302 engine and two MAN E2842 LE322 engines. The units were fuelled with post-processing gas containing 85-95% of hydrogen [2], and in 2019, they gained over forty thousand operating hours, proving very high reliability. Another interesting example of commercial application is the Perkins 4016-61TRS2 engine delivered in March 2022 to operate on pure hydrogen (Fig. 4). The unit is able to generate 1 MW of electric power and 1 MW of heat or 750 kW in chill water to a local factory will also be used as peak shaving solutions for local wind farms. During the overproduction of electricity from the wind farm, the surplus electricity will be used to produce hydrogen using the process of water electrolysis. The hydrogen will be stored in high pressure tanks and can be later used to generate electricity when there is a lack of power in the system or electricity price is attractive enough.

The MUZG system has been installed commercially since 2017 and has also proved its unique flexibility for gas fuels with variable properties. The engines with the MUZG system work well fuelled with syngas (gasified sewage sludge) containing about 40–45% of hydrogen and also other fuels with low quality, like coalmine gas for instance. Those engines also proved their high durability and gained over sixty thousand running hours so far (Fig. 11).

The theoretical average annual availability of industrial gas engines is 8650 hours [4, 9, 12], which is based on ideal operation when all maintenance actions are done as scheduled, with no delays, unexpected stops, and failures. In reality, such number is extremally hard to reach, and typical industrial gas engine has the real average annual availability of about 8000 hours, and well maintained and carefully operated engines with good and stable gas quality can reach 8350–8400 hours of average annual availability.

The engines with the MUZG system reached an average 8100 hours even though the gas quality was low with many impurities and significant fluctuation of gas composition. It is also important to mention that units operating on waste fuels or by-products are treated the same way as fuel, so the owner usually doesn't pay much attention to careful operation or regular maintenance with the required schedule.

The engines equipped with the WUZG system reached even 8600 hours of average annual availability even though the gas composition was not stable and fuel was not purified at all.

These impressive results were possible because both systems have the unique functionality of continuous combustion process monitoring and can react if improper operation is detected to adjust relevant settings (the WUZG system can do it even for each cylinder separately).

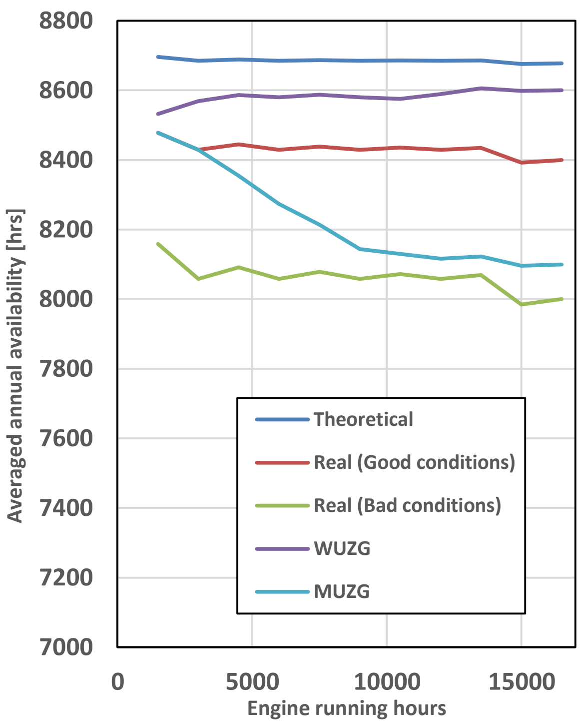

Fig. 11. Comparison of reliability of typical industrial gas engines and the engines with the MUZG and the WUZG

6. Conclusions and future steps

The MUZG and the WUZG systems are universal can be installed on any industrial gas engine and, once installed, they improve engine operation flexibility and performance, even when the engine is operated on conventional fuels. Better performance is achieved mainly due to better detection of knock margin but also thanks to continuous monitoring of engine condition and corrective settings implied for the whole process, from mixture formation to combustion. All additional sensors used to ensure that the gas-air mixture is carefully prepared and the combustion process is well monitored together with fast signal processing help to operate on fuels with variable properties or low quality when the change in control can be applied within one single engine cycle.

The MUZG and the WUZG systems are especially designed to control the combustion of hydrogen based fuels. The functionality of the systems allows the use even pure hydrogen and still to control combustion properly i.e. to prevent from knock, to limit combustion temperatures, to control flame speed etc. All of these are done by early detection of knock or misfiring tendencies, exhaust temperature rise or fall, and once it is detected, counteraction is applied already in the following engine cycle. The WUZG system allows additionally to control of each cylinder separately with the individual mixture composition or with temporary cylinder deactivation if the combustion process is hard to control and leads to potential cylinder failure.

The monitoring also enables save operation of the engine. Even small variations from the desired engine operation can be detected and various corrective actions can applied before the process reaches a serious level or damage occurs. This helps to avoid situations when the engine's available power is limited, or the engine needs to be stopped due to an operation warning or alarm signal. All of these are reflected in the annual average availability of the engines equipped with the MUZG or the WUZG system regardless of fuel type and quality that were used.

The combined MUZG and the WUZG system brings additional operational flexibility, as the engine control system can switch from one fuel supply system to another. The MUZG system gets priority when fuel has low pressure low hydrogen content and the WUZG system is preferred when gas pressure or hydrogen content are relatively high.

As the mentioned systems have high potential for various applications there are many further development projects already ongoing or planned. The combined MUZG-WUZG system will be extended to enable the use of other gaseous hydrocarbons blended with hydrogen. The MUZG system can be used for bi-fuel engines fuelled with oil fuel (biodiesel for instance) and gas fuel (bio-methane for example), which will create a very reliable and carbon dioxide neutral solution for independent power generation with unique operational flexibility and loading performance not observed in typical industrial gas engines. And finally, the WUZG system can also be used for bi-fuel engines combining the combustion of biodiesel with hydrogen or for other fuels, such as alcohols. Basic tests of that system has already been started and the first results are promising, but the solution is still far from final implementation.

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