DOI: 10.13009/EUCASS2017-125

Experimental Evaluation of the Pollutant and Noise Emissions of the GTCP 36-300 Gas Turbine Operated with Kerosene and a Low NO_X Micromix Hydrogen Combustor

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Abstract
Auxiliary and Ground Power Units are major sources of noise and pollution at airports. Aachen University of Applied Sciences researches low-emission combustion of hydrogen and has developed the Micromix technology with proven low emission properties. The paper presents the exhaust gas and noise emission analysis comparing kerosene with MMX hydrogen combustion in the GTCP 36-300. The MMX combustor with hydrogen reduces the exhaust gas emissions significantly. The overall noise of the core engine is reduced, too, with higher sound-pressure-level magnitudes in the frequency range between 1000 Hz and 5000 Hz, the range most sensitive in human hearing.

1. Introduction

Auxiliary Power Units (APU) and Ground Power Units (GPU) are a major source of noise and pollutant emissions at airports. Both, aviation and the power generation industry have need of efficient, reliable, safe and low-pollution energy conversion systems. Therefore, gas turbines play a decisive role in long-term high power application scenarios with low emissions. Due to the finite resources of fossil fuels, hydrogen and hydrogen-rich gas-mixtures have great potential as renewable and sustainable energy sources [1]. Operating a common industrial gas turbine with gaseous hydrogen needs to consider some important major impacts on the complete gas turbine system. Besides combustion technology and related exhaust gas emissions, modifications of the gas turbine control and fuel metering system have to be applied to guarantee safe, rapid and precise changes of the engine power settings [2]-[7]. Against this background, the Gas Turbine Section of the Department of Aerospace Engineering at Aachen University of Applied Sciences (AcUAS) works in the research field of low-emission combustion chamber technologies for hydrogen-rich fuels in gas turbines. The research and development activities cover low emission combustion chamber design, system integration, and fuel system modification including control software adaption. Major modifications on the gas turbine structural and control architecture are thereby avoided. The impact on the control and fuel metering strategy of the gas turbine are absorbed by minor changes in the engine controller software and the metering unit without any mechanical changes to the gas turbine. In [4]-[7], the successful implementation of a metering unit for gaseous fuels, the modification of the fuel control system and the re-programming of the VECB (engine controller) for the use of hydrogen instead of kerosene are described. In [5] the start-up and acceleration behaviour of the APU with hydrogen is shown. [8] describes the successful conversion of the GTCP 36-300 from liquid kerosene to gaseous hydrogen and to gaseous methane, and describes the control behaviour at different loads, its acceleration and deceleration behaviour without modifications of the fuel nozzles or any changes of the gas turbine mechanical structure or the combustion chamber. When hydrogen is used as fuel without modification of the combustion chamber, even higher NO_x emissions arise compared to kerosene. The application of Micromix (MMX) reduces the resulting NO_x of hydrogen combustion significantly [8], [12]-[14]. To investigate the feasibility of alternative gaseous fuels under real engine operation conditions, the aircraft Auxiliary Power Unit (APU) Honeywell/Garrett GTCP 36-300 is used as experimental test rig at AcUAS (Figure 1).

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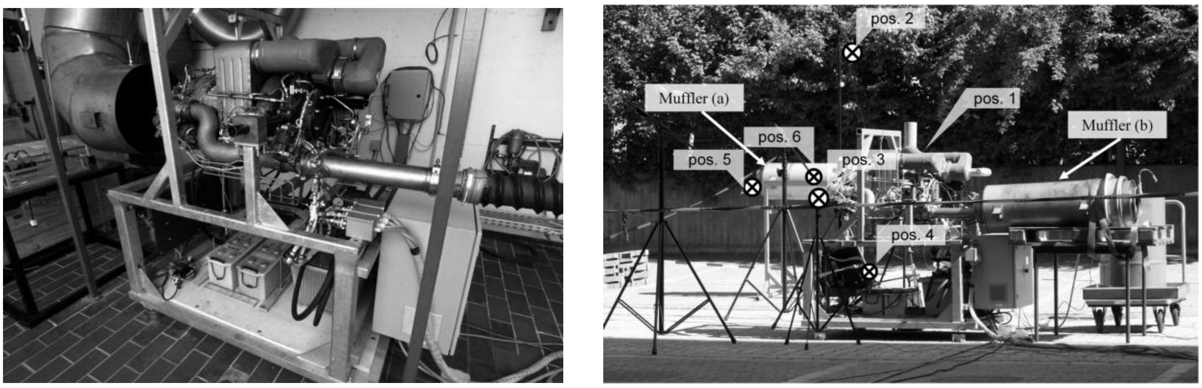

Figure 1: GTCP 36-300 at exhaust emission test stand (left) and during free-field noise measurement (right)

The GTCP 36-300 is a single spool gas turbine engine with a single-stage radial compressor and a single-stage radial turbine. The combustion chamber generates about 1.6 MW thermal energy that is converted to shaft power to drive an auxiliary generator and an additional single-stage radial load compressor. The nominal power output is up to 335 kW. The combustion section consists of an annular reverse flow combustion chamber. In its original configuration, six circumferentially distributed fuel nozzles spray liquid kerosene into the chamber. To operate the APU with gaseous hydrogen, the kerosene nozzles are replaced by a low NO_x MMX combustor, and an additional metering unit for gaseous fuels is implemented. Furthermore, a hydraulic system is added to perform hydraulic functions, which are normally achieved by kerosene as hydraulic medium.
The GTCP 36-300 is a rotational speed controlled gas turbine engine. The conversion from kerosene to hydrogen-rich gases bases on the concept of feeding the same requested amount of thermal heat into the combustion chamber regardless which fuel is used. Similar gas turbine operation characteristics are achieved for different fuels in all modes of operation by maintaining the designated rotational speed for each load condition. Since hydrogen and kerosene have very different properties, e.g. heating value, air requirement, flammability range and flame speed, the change of the fuel has an impact on the combustion characteristics and the thermodynamic gas turbine cycle, which influence the engine control behaviour [8].

2. Emission Testing

2.1 Set-Up and Procedure

The MMX combustion principle is developed and optimized at AcUAS since the European research projects EQHHPP [9] and CRYOPLANE [10]. The use of hydrogen as a fuel burned with air in diffusion- or premixed-type combustors reduces the emissions to only water vapor and nitric oxides (NO_x) [11]. The principle has been successfully applied for the combustion of hydrogen and hydrogen rich syngas (H_2-CO) and adapted in conventional gas turbines also at elevated pressures with the proof of significant NO_x emission reduction [12]-[14]. The DLN Micromix principle significantly reduces the formation of nitric oxides by miniaturizing the reaction zone through the creation of multiple micro diffusion-type flamelets with a typical size of 30-40 mm in length. The mixing process prior to combustion is based on the phenomenon of jet-in-crossflow (JICF). Fuel is injected perpendicular into the airflow and burned in miniaturized, diffusion-like flames. The general principle of jet-in-crossflow-mixing is depicted in Figure 2.

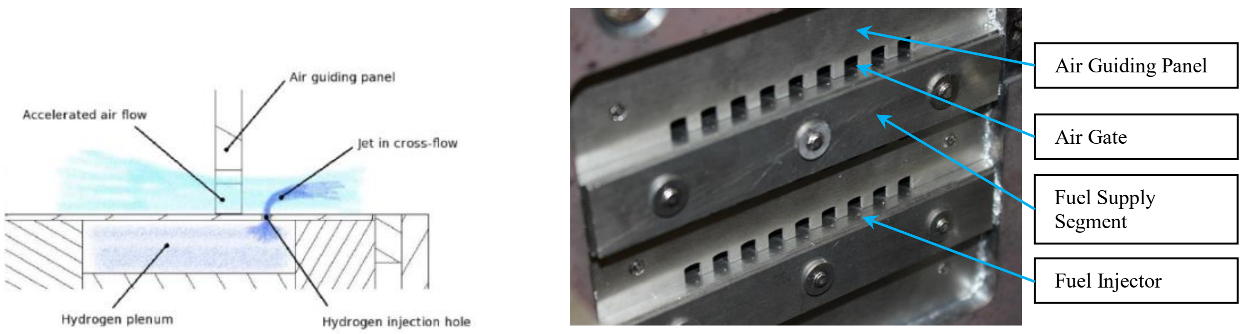

Figure 2: Section view of a Micromix combustor

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With an appropriate choice of the combustion chamber design, an optimized mixing of fuel and air and aerodynamic stabilization of the combustion process is obtained, Figure 3. The miniaturization of the flamelets leads to a significant reduction of NO_x emissions due to the reduced residence time of reactive species in the high temperature domain. Since no premixing of fuel and oxidizer prior to injection occurs, the risk of flashbacks is avoided.
In Figure 2 (right) the structural layout of a typical Micromix combustor is depicted and Figure 3 (left) shows a full-scale combustor as it is installed in the GTCP 36-300. Fuel is distributed through the fuel supply segments and injected through small nozzles into a crossflow of air. The fuel supply segments and the air guiding panels form a system of concentrically arranged rings which both act as bluff bodies to form counter-rotating vortex pairs during operation of the combustor (Figure 3, right). The vortex proportions are designed to facilitate flame stabilization and to prevent adjacent flames from merging with each other. Merging of adjoining flames would result in the formation of a reduced number of large scale flames increasing the residence time of NO_x precursors in the hot reaction zone and significantly promoting NO_x formation.

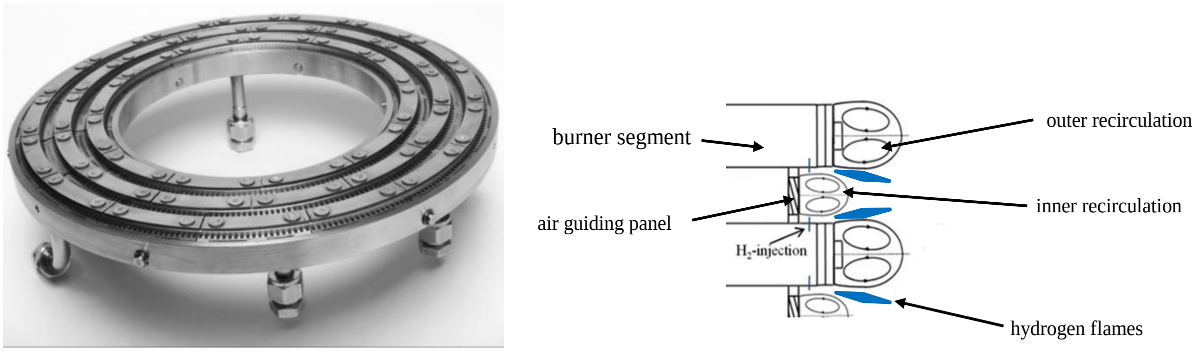

Figure 3: Full-scale Micromix combustor (left) and schematics of aerodynamic flame stabilization (right)

The MMX combustor of the GTCP 36-300 (Figure 3, left) has about 1600 small jet-in-crossflow injectors equally distributed over the annular combustor cross-section. It is implemented into the combustion section of the GTCP 36-300 replacing the original kerosene fuel nozzles. Besides the previously mentioned modification of the control software and the metering unit, no more changes are performed. Hydrogen is supplied from pressurized bottles with a combustor inlet pressure of around 16 bar and an inlet temperature of about 300 K. A heated and rotating isokinetic probe takes samples over the complete exhaust duct cross section. The extracted samples are supplied via the probe to the analysis modules of the gas analysis system ABB Advanced Optima AO2020 by heated tubing, which is designed to avoid concentration changes of the different components within the exhaust gas sample, and condensation of water in the tubing that could influence the analysis results. The gas sample is directed through a gas dehydrator to each analysing module by heated tubes and hoses under controlled pressure conditions. The Advanced Optima exhaust gas analysis system determines the amount of unburned hydrocarbons (ABB Multi-FID 14) during kerosene testing, of unburned hydrogen (ABB Caldos 27) during hydrogen operation, of the concentration of O_2 (ABB Magnos 206) and the amount of CO and CO_2 (ABB URAS 26) during all runs. For the determination of NO_x (i.e. NO and NO_2), an Eco Physics CLD 700 EL is used and directly connected to the hot exhaust gas sample. Internal hot tubing and particle filters in the CLD device allow analyses without pre-processing of the gas sample and prevent water condensation. Before each testing, all exhaust gas analyser devices are calibrated using zero-point calibration gases and defined reference-point calibration gases.

2.2 Results of NO_x Emission Analysis

Figure 4 presents the measured NO_x-emissions over the overall power output of the GTCP 36-300 from idle mode to full load operation, when kerosene and hydrogen are used as fuels. In its original kerosene operation, the NO_x emissions rise with increased power output as expected along with the increase of heat in the flame tube of the combustion chamber. The figure also compares the resulting NO_x-emissions of different fuel configuration with hydrogen already presented in [6] to highlight the need of optimized hydrogen combustion technologies. The curve indicated as "H2 Nozzles" shows the NO_x characteristics, when simply the six kerosene fuel nozzles are replaced by six gas nozzles to inject gaseous hydrogen. A stable operation of the engine is also ensured, but the six large hydrogen flames in the combustion chamber form large areas of high thermal load, where the formation of thermal NO is heavily intensified due to an increased residence time of the reactants in the hot flame region. In this nozzle configuration, the NO_x emissions are even higher than in kerosene operation. In comparison, the optimized MMX hydrogen combustor ("H2 MM_CC") shows significantly reduced NO_x-emissions over the whole operating range of the gas turbine. Due to the

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utilized flame miniaturization and the multiplication to up to approximately 1600 micro-flamelets instead of six large-scale flames, the MMX combustor homogenizes the temperature distribution over the combustor cross section and significantly lowers the residence time of the reactants in the hot flame regions at comparable gas turbine operational conditions. The result is a significant reduction of NO_x below 10 ppm up to full-load. This clearly points out the need of adequate combustor modifications for low NO_x hydrogen operation that can cope with the high reactivity and heat release during hydrogen combustion.

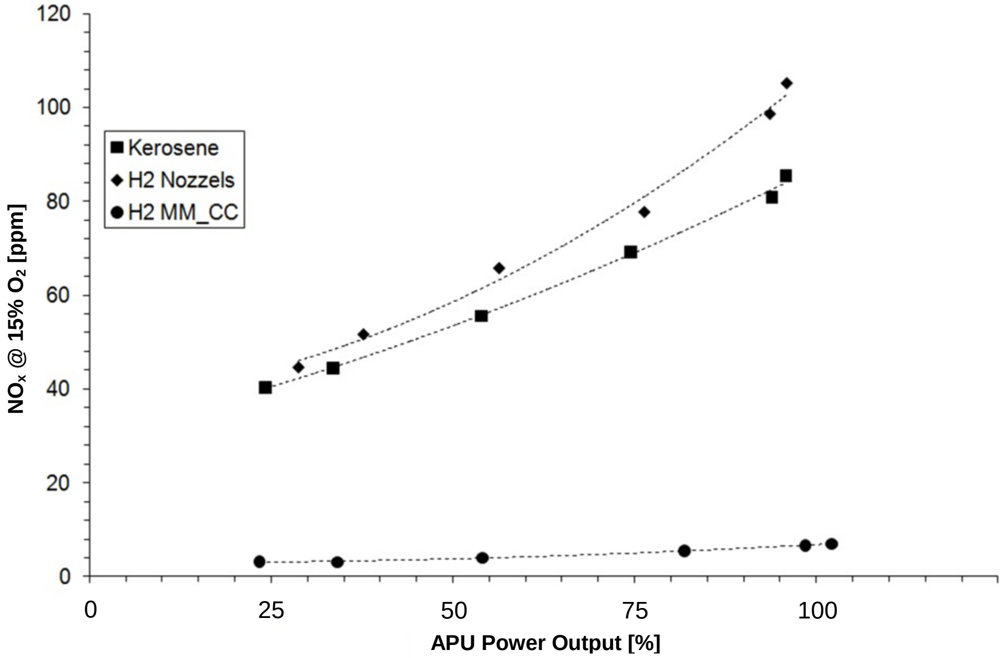

Figure 4: NO_x-emissions against APU power output

3. Noise Testing

3.1 Set-Up and Procedure

The noise emission analyses of the GTCP 36-300 both in MMX hydrogen and in conventional kerosene operation take place in a free field set-up that is nearly free of reflection or absorption. The microphones are positioned around the gas turbine with a distance of $d = 1m$, Figure 5. The microphone positions 1 to 4 are placed within a horizontal plane on the height of the rotational axis of the APU, the microphone positions 5 and 6 are arranged in a 45° angle to record the exhaust noise. During the testing, two mufflers are installed at the bleed air outlet and at the exhaust gas outlet. The experiment aims to compare the differences of the noise characteristics, when the same gas turbine is driven by different combustors and fuels. Therefore, a damping of the air jet noise from the bleed air feed and the exhaust gas outlet that could influence the results is reasonable. The used mufflers are standard aviation mufflers that are normally implementation in the aircraft.
For all measurements, the APU is operated both in idle mode and in full load mode.

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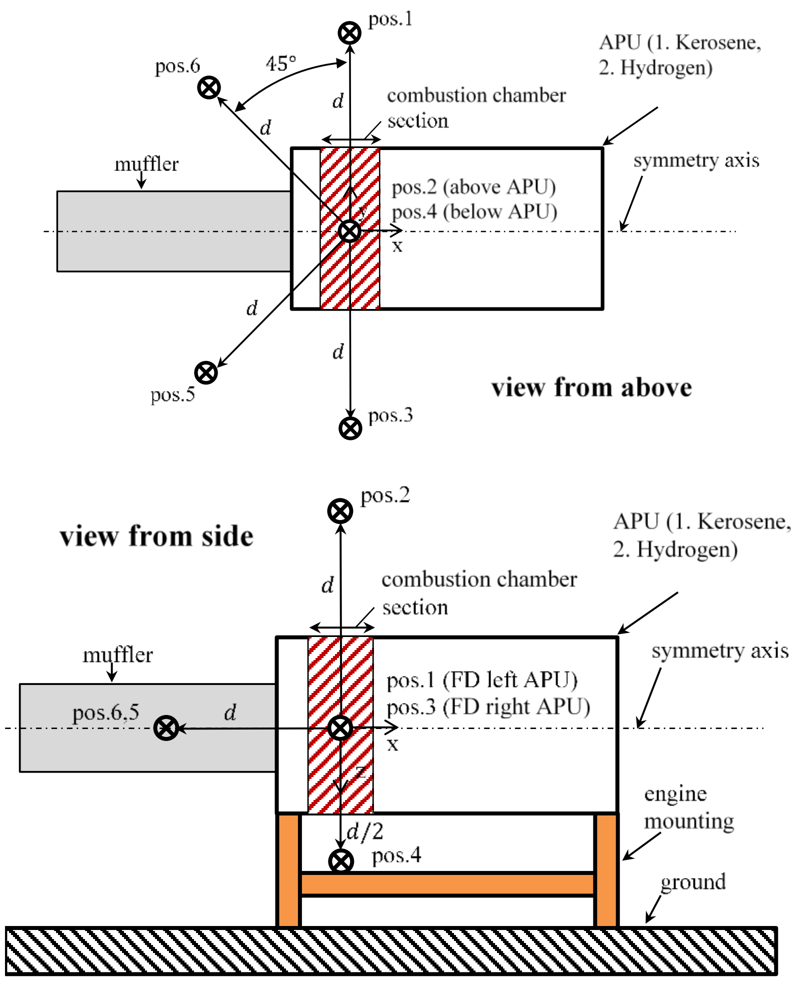

Figure 5: Setup of the noise analysis of the APU GTCP36-300

The recording of the sound pressure is accomplished by six omnidirectional microphones Gefell M360. The voltage signals from the microphones are sampled and recorded by the Mark II PAK system from Müller BBM including two modules with different sampling rates and four channels each. Two channels are used to log the rotational speed signals from the inductive measurement sensors of the gas turbine and six microphones record the sound pressure in the form of electrical voltage. The sampling frequency is about 56 kHz. Considering the Nyquist theorem, a sampling frequency of $f_{log} = 2.56\ f_{max}$ results, i.e. a maximum of 8000 Hz in the octave band and a maximum third octave band of 16000 Hz of an octave or a third-octave spectrum.

3.2 Results of the Noise Analysis in Idle Mode

Figure 6 shows the recorded data of the sound pressure over the frequency for the hydrogen and the kerosene run in idle mode at each microphone position. The diagrams show an almost similar characteristic for kerosene and hydrogen both, but when the frequency range between 1000 Hz and 5000 Hz is regarded, the broadband noise of hydrogen has a higher sound pressure level compared to kerosene at all microphone positions.
This specific frequency range of 1000 Hz – 5000 Hz coincides with the range where the human hearing is most sensitive. Therefore, the noise of the gas turbine fueled with hydrogen can be perceived as more annoying compared to the kerosene operation. The difference between both fuels is about 6 dB on average, i.e. almost a doubling of the sound pressure in hydrogen operation in this frequency range. As a result of a lower temperature profile in the combustion process with hydrogen [8], flow velocities are smaller with kerosene. On this account, turbulences are larger with hydrogen and hence, the broadband noise in the range of deeper frequencies is more intense.
With increasing frequency, the difference of the sound pressure level between both fuels decreases and almost vanishes. At a frequency of 16 kHz a haystack starts, which is a result of the interference between the load compressor and the power compressor

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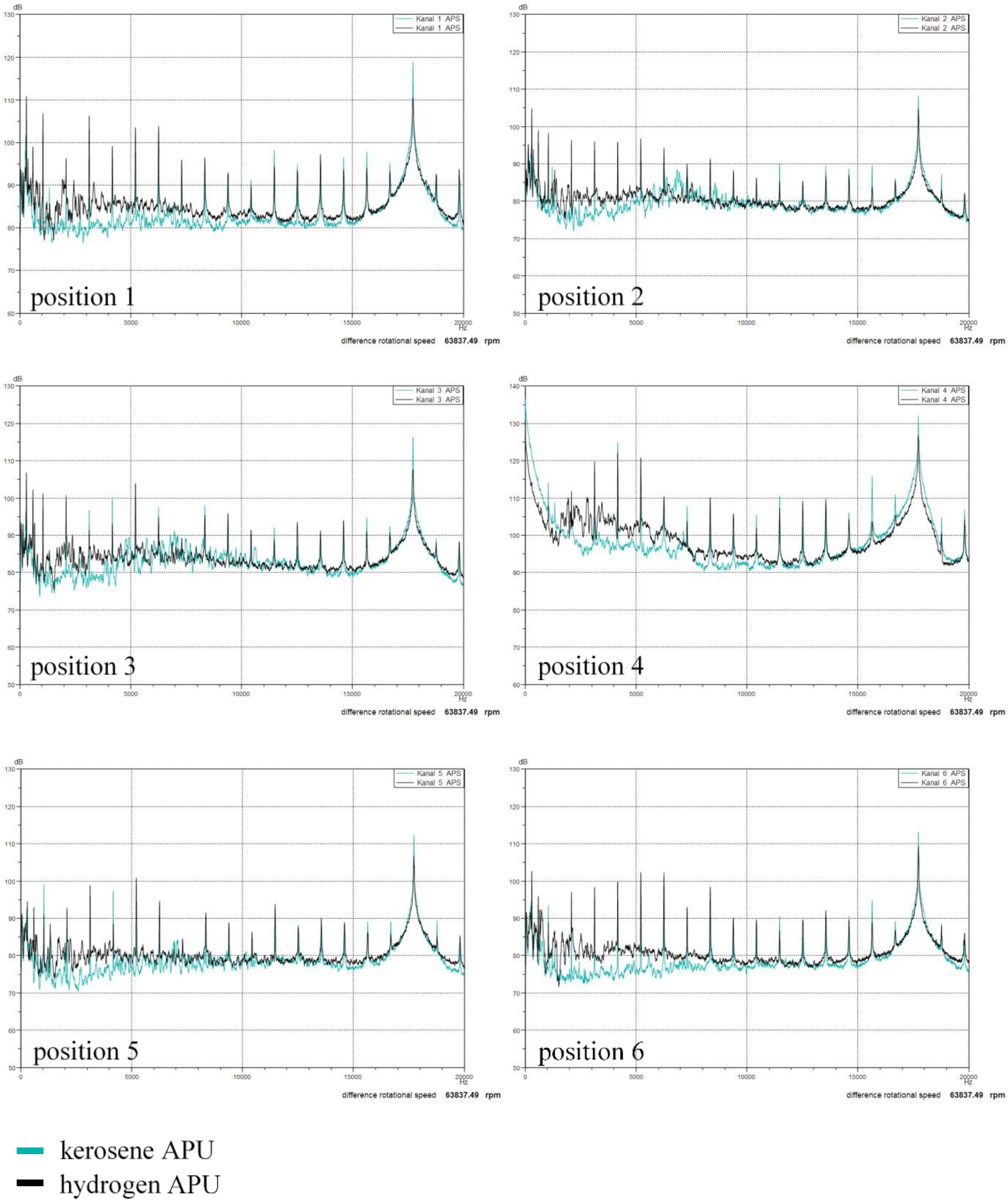

Figure 6: Comparison between hydrogen and kerosene idle mode

3.3 Results of the Noise Analysis during Full Load

In full load mode (Figure 7), the effect of the broadband noise in the frequency range between 1000 Hz and 5000 Hz that is described above, is smaller than in idle mode. This can be explained with the flow velocities that increase with the higher rotational speed during full load. In hydrogen operation, the gas turbine requires a reduced temperature change to increase the rotational speed compared to the use of kerosene. For that reason, the amplitude of the sound pressure level equalizes more and more with increasing rotational speed. At the high rotational speed of about 64000 rpm, shockwaves produce high pressure fluctuations creating a lot of small turbulence areas. The general increase of the turbulence intensity with increasing rotational speed at full load leads to total sound pressure levels of the broadband noise that are higher than in idle mode. The impression of an asymmetric haystack at position no. 4 is

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created due to the superposition of the broadband noise of the turbulence within the APU and the haystack of the compressors that stays nearly the same in both modes.

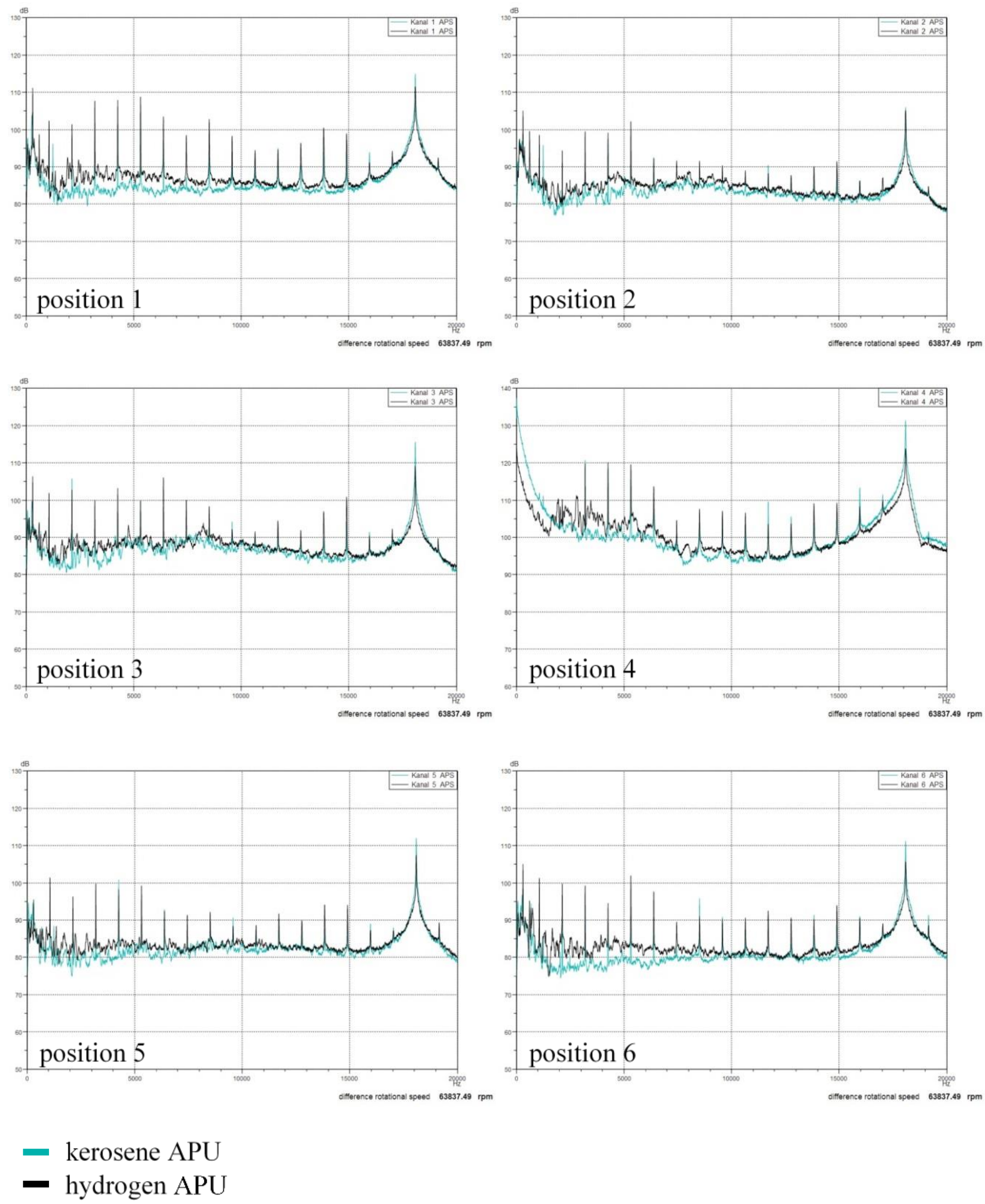

Figure 7: Comparison between hydrogen and kerosene in full load

In Figure 8, the sound pressure level over frequency spectrum of idle mode is laid over the spectrum of full load mode with an adjustment of the x-axis so that the peaks of the haystacks are at the same location and can be compared with each other. The curves in idle and full mode vary strongly in the magnitude of the broadband noise although the trend stays nearly the same. Figure 8 also shows clearly that when the APU is operated in idle mode, the difference in the important range of 2000 Hz to 5000 Hz is higher than in full load which is a reason for less smoothness and larger turbulences of the flow.

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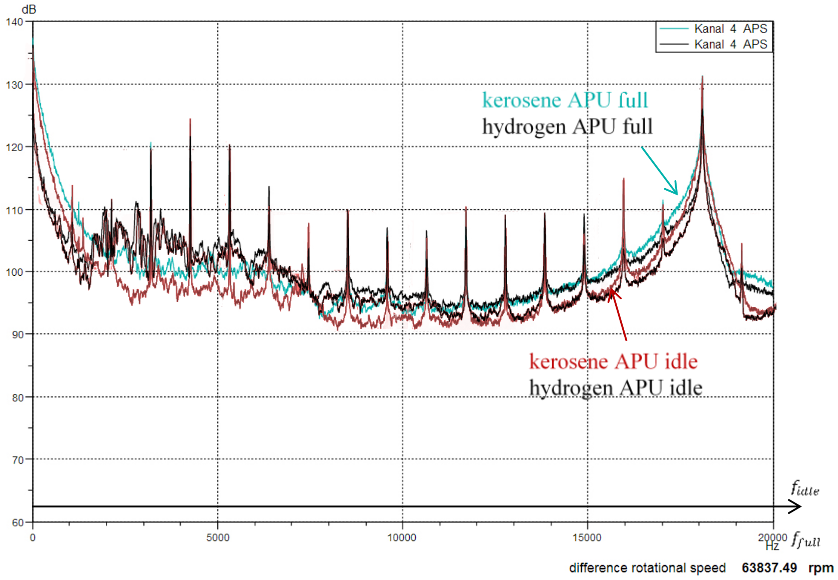

Figure 8: Comparison between full load and idle mode (hydrogen and kerosene) at position no. 4

3.4 Averaged Sound Pressure Level and Third-Octave Band Spectra

Comparing the noise emissions of the kerosene and the hydrogen operation, the subjective impression is created that the hydrogen operation is perceived louder than the kerosene operation. To analyse the average sound-pressure-levels, the following table lists the recorded sound-pressure-levels of the kerosene and the hydrogen run at each microphone position:

Table 1: recorded sound pressure levels, calculated overall averaged sound pressure levels

	Kerosene		Hydrogen	
i	idle: $L_{p,i,idle,k}$ [dB]	full load: $L_{p,i,full,k}$ [dB]	idle: $L_{p,i,idle,h}$ [dB]	full load: $L_{p,i,full,h}$ [dB]
1	121,5	121,4	120,2	121,6
2	114	116,1	114,1	116,9
3	119,7	121	117,7	120,1
4	136,98	138,38	131,08	130,58
5	115,5	117,1	114,8	116,4
6	116,6	117	116,5	116,5
overall averaged sound pressure level	$\overline{L_{p,idle,k}}$, [dB]	$\overline{L_{p,full,k}}$ [dB]	$\overline{L_{p,idle,h}}$ [dB]	$\overline{L_{p,full,h}}$ [dB]
	129,5	**130,45**	**123,82**	**123,9**

Table 1 shows that in fact at nearly all microphone positions the hydrogen operation creates a lower sound pressure level than the kerosene operation. This is astonishing, because humans subjectively perceive the hydrogen operation as noisier than the kerosene operation. The reason is found in the increased sound emissions in the frequency range between 1000 Hz and 5000 Hz, Figure 9.

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Figure 9: Comparison of the third-octave band spectra's of hydrogen and kerosene run

Regarding the third octave bands containing the averaged sound pressure level for the specific frequency bands for each microphone position, the hydrogen operation is less noisy in the deeper frequency ranges. The effect on the human hearing still exists, but due to the fact that many high peaks are averaged with the lower sound pressure levels, the total sound pressure level for the third-octave bands are lower. The subjective impression of the louder hydrogen operation remains because of the relatively high peaks in the sensitive frequency range of a human, but Figure 9 clearly shows that the hydrogen operation is objectively less noisy.
At microphone position no. 4, the total sound pressure level differs about 5.9 dB in idle mode and 7.8 dB in full load mode, while on all other positions the difference is small. A reason for this deviation can be the fact that the combustion temperature of hydrogen is lower and hence there are slower flow velocities that lead to less turbulence on the air inlet of the gas turbine than with kerosene. The magnitude of the change of the turbulences has to be very high, so that a doubling of the sound source results.

4. Conclusion

An experimental analysis has been performed to compare the operation of the auxiliary power unit GTCP 36-300, when it is fuelled with kerosene and when it is operated with the innovative hydrogen Micromix (MMX) combustor.

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The emission analysis shows that the MMX combustion technology can significantly reduce the pollutant emissions with hydrogen and the noise measurements show that the overall noise is reduced, too, when the MMX hydrogen combustor is applied.
However, in case of noise, the hard test data needs to be regarded in relation to psychoacoustic effects. The MMX hydrogen combustion creates higher sound pressure levels in the critical frequency range of the human hearing and gives the impression that it is louder than the operation with kerosene, while the overall averaged sound pressure levels are decreased. There is an increase of the magnitude of the sound pressure levels in the frequency range between 1000 Hz and 5000 Hz in hydrogen operation. This leads to the subjective impression in human hearing, that the gas turbine noise is louder when it is fuels with hydrogen and operated with the MMX combustor.

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