MODIFICATION AND TESTING OF AN ENGINE AND FUEL CONTROL SYSTEM FOR A HYDROGEN FUELLED GAS TURBINE

PROPULSION PHYSICS – AIR BREATHING I

H. H.-W. Funke[1) S. Börner[2)
Aachen University of Applied Sciences, Department of Aerospace Technology
Hohenstaufenallee 6, 52064 Aachen, Germany

P. Hendrick[1)
Université Libre de Bruxelles
Avenue F.D. Roosevelt 50, 1050 Brussels, Belgium

E. Recker[2)
Royal Military School of Belgium
Avenue de la Renaissance 30, 1000 Brussels, Belgium

1) Professor 2) research engineer

Abstract

The control of pollutant emissions has become more and more important by the development of new gas turbines. The use of hydrogen produced by renewable energy sources could be an alternative. Besides the reduction of NO_x-emissions emerged during the combustion process another major question is how a hydrogen fuelled gas turbine including the metering unit can be controlled and operated. This paper presents a first insight in modifications on an Auxiliary Power Unit GTCP 36-300 for using gaseous hydrogen as an engine fuel. For a safe hydrogen operation the metering of the hydrogen has to be fast, precise and secure. So the quality of the metering unit's control loop has an important influence on this topic. The paper documents the empiric determination of the PID control parameters for the metering unit.

1. Introduction

Gas turbines as reliable, efficient, long-life and light-weight propulsion systems will also be part and parcel of the future aircraft development. Due to the narrowness of the fossil fuels and the international effort of reducing the environmental pollution there is inherent need for alternative renewable fuels. A possible alternative is – besides synthetic fuels – the application of hydrogen, if it is produced by using renewable energy sources. (E.g. sun and wind energy)

By the use of hydrogen as a fuel for gas turbine engines there are two major questions which have to be answered before the adaptation in aircraft industry. The first one: How can hydrogen be burned efficient and stable under variable operations with minimum possible NO_x-emissions while the safety risk of flash back is eliminated? The second: Which modifications for the control system and the fuel metering system have to be realised in order to allow the rapid and precise changes of engine power level as necessitated by aircraft operation conditions?

Since years Aachen University of Applied Sciences (ACUAS) is working on to solve these two major questions [1,2]. In order to achieve a substantial reduction of the NO_x-emissions during the combustion process the micromix burning principle has been developed by the ACUAS. This micromix burning principle for gaseous hydrogen [3,4,5] is based on the fluid mechanic phenomenon of combustion on jets in cross-flow.

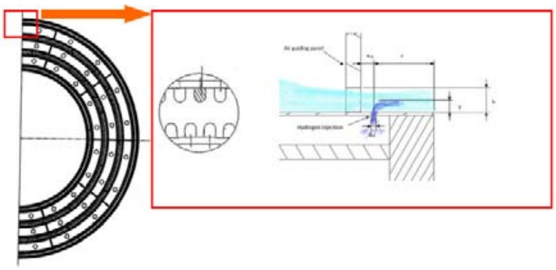


Figure 1: Micromix combustion principle

In the presented case of the micromix burning principle the hydrogen is injected vertical in the airflow. The hydrogen burns directly after the jet in cross-flow interaction in multiple miniaturized flames. The current hydrogen chamber with about 1.6 MW of thermal power counts nearly 1600 miniaturized flames (Fig.1). Through this miniaturization of the flame length and flame temperature the burning principle archives a lowering of the reaction temperature and a reduction of the residence time of reactants in flame region and reduces therefore the NOx- formation [1].
Various scientific investigations have been done from the experimental [4,5] and from the numerical point of view in order to understand the phenomena of the principle and their influence on the NOx- formation. Due to the fact that this hydrogen burning principle is designed as a non premixed concept there is an inherent safety against flashback.

Besides optimizing the burning principle in lowering NOx- emissions the control system and the metering unit of the gas turbine has to be modified and improved. Basic idea is to modify a kerosene driven engine into a hydrogen fuelled gas turbine. The operability of the hydrogen fuelled gas turbine should be as far as possible similar to the kerosene one. With the change form kerosene to hydrogen also a change from a liquid to a gaseous fuel accompanies. Due to this fact and to the strict security requirements for the hydrogen application the control and metering system has to be modified.
One basic requirement to the control system is the fast and precise metering of the hydrogen for a safe ignition and for the different operating conditions of the gas turbine. In addition the control loop has also to consider the mechanic and hydraulic behaviour of the metering system.

With the implementation of the modified and improved control and metering system the PID parameters of the control loop has to be set in order to guarantee the designated and secure operating / starting sequence of the hydrogen engine. For testing the adjustments first ignition tests are presented.

2. Engine and fuel control modification

2.1 Engine and test rig

For the experimental work there are two auxiliary power units (APU) GTCP 36-300 available at the university. The single shaft engine is used in different aircrafts, such as the AIRBUS A 320, and provides electrical and pneumatic power to the aircraft via a generator and an extra load compressor. The main components of the engine are the single stage radial compressor, an annular combustion chamber consisting of 6 single fuel nozzles and a single stage radial turbine. The engine is controlled by the Versatile Engine Control Box (VECB) built by DIEHL Aerospace GmbH. The APU can produce up to 370 kW during main engine start operation (MES). In order to compare the influence of the changeovers for the hydrogen application on the engine behaviour and on the exhaust emissions one APU is modified, the other one is still in kerosene application. To meet the requirements of testing the gas turbine outside the laboratory for possible application in industrial environment the test rig is built as mobile test rig (Fig.2).

Figure 2: APU GTCP 36-300 in mobile test rig

2.2 Hydrogen modifications

To run the engine with hydrogen instead with kerosene several modifications have to be done. The hydrogen cannot serve as hydraulic medium for the load compressor guide vane actuator. Therefore an external hydraulic unit assumes these functions. The change of the combustion chamber will be done in two steps. To get first impressions of the hydrogen fuelled gas turbine behaviour the kerosene nozzles will be exchanged to gaseous ones. From prior measurements is known that this change will not have a significant impact on the NOx-emissions instead of kerosene [1]. Later on, when the NOx-formation influencing parameters are evaluated and conduct to the improved combustion chamber design, a new combustion chamber based on the micromix principle will be installed in the engine. Secondly the fuel metering system for gaseous hydrogen and the control software have been designed and improved according to former control systems [6].

2.3 The control unit

The optimized and hydraulically operated hydrogen metering unit is shown in figure 3. The hydrogen mass flow is metered by a valve which is appropriated for the hydrogen application. This valve is traversed by a hydraulic cylinder whose position is dimension for the hydrogen mass flow and is given back as controlled process variable to the control unit. The amount and velocity of the cylinder's operation is metered by hydraulic MOOG valve. This valve constitutes the central unit of the hydrogen metering unit and is actuated by the control unit.

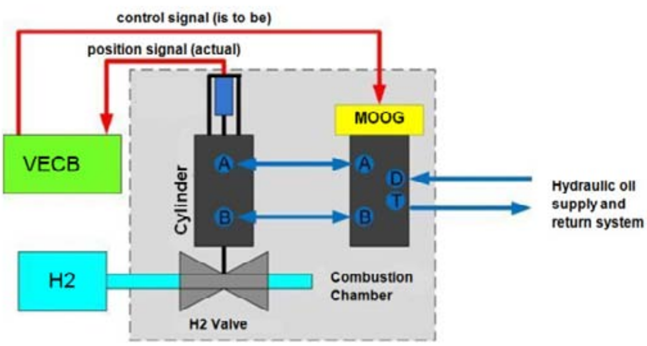


Figure 3: The hydrogen metering unit

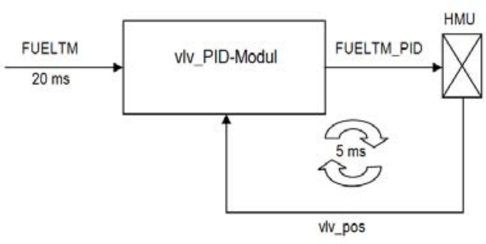


Figure 4: The control loop

Due to the dynamic need of the engine a very fast metering unit was designed and built. Besides the fuel metering valve there are other vales important for security reasons: In the case of emergency or malfunction of the hydrogen engine the main fuel supply will be stopped. Additionally it is necessary to scavenge the fuel pipes before and after each engine run with nitrogen.

2.4 Control software

The test engine and the metering unit are controlled and operated by the Versatile Engine Control Box (VECB). The box is integrated in the mobile driver's control desk. The major function of the controller is to keep the engine speed constant for each load condition by varying the fuel quantity, load compressor guide vanes and the surge control valve. The two essential operating conditions are:

- **ECS**: Environmental Control Supply. The APU delivers compressed air for the air condition.
- **MES**: Main Engine Start. Start of the main engines. Maximum power output of the APU.

The control of the engine proceeds in to different parts. During the starting sequence an acceleration from zero to 95 % speed including the ignition is controlled by the VECB. Then the closed loop engine control takes over for all operating conditions of the APU. The metering of the hydrogen to the combustion chamber is controlled as a function of speed. Each speed step is attributed an valve opening position and therewith a hydrogen mass flow. Between two speed steps the valve's opening position is interpolated. An improvement is that the VECB integrated controls both - the engine and metering unit. Therefore an additional PID (vlv_PID-Modul) controller has been implemented in the VECB and its software (Fig.4). So an additional and separate control loop for the metering unit can be avoided. The main control loop software of the engine sends the requested opening position to the vlv_PID-Modul. The fact of the PID-Modul is to assure the required hydrogen valve position by operating the MOOG valve. A position encoder measures the actual position of the valve (vlv_pos) and reports it to vlv_PID-Modul. If there is a spread between the actual and the required valve position the vlv_PID-Modul sends a control current (FUELTM_PID) to the MOOG valve in order to reach a minimization of the spread. The clocking of vlv_PID-Modul control loop is 5 ms. Whereas the main control loop software's clocking is 20ms. Additionally there are also a few other security changes in the engines control software necessary for the hydrogen application. For example a Dry Crank has been implemented before the engine starts in order to archive that there is none unregulated hydrogen content available in the combustion chamber.

3. Empiric determination of the PID control parameters for the metering unit

3.1 Requirements on the metering unit's control loop

With the effort to implement a hydrogen driven gas turbine with the same operating characteristics as a kerosene fuelled engine also the main needs of the control loop are defined. The main operating characteristics and requirements of the APU, especially during ignition and acceleration, are taken from a kerosene operation (Fig. 5). Also the FUELTM-value over time which is unit of measurement for the requested kerosene mass flow is shown in the diagram.

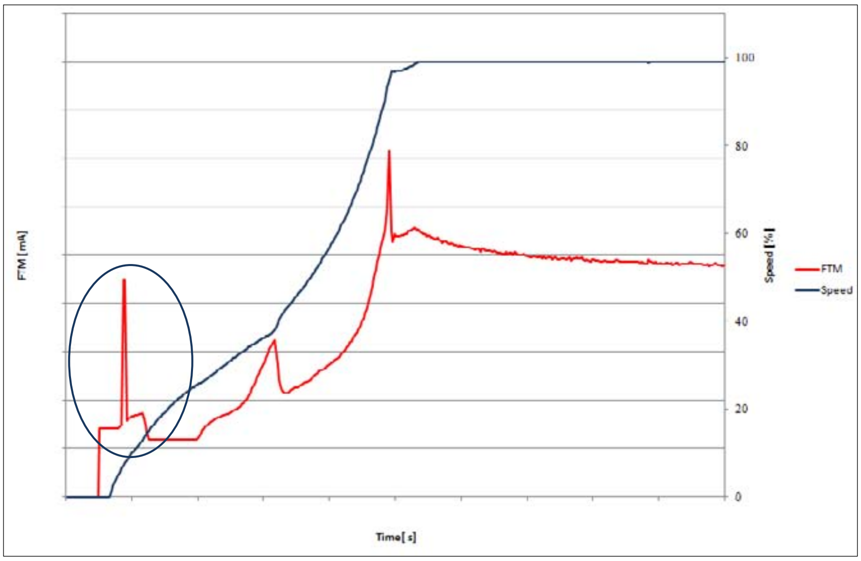


Figure 5: Kerosene reference run

In order to overpower the turbine's starting torque and continuing the acceleration the control loop increases the FUELTM-value (blue border). For the hydrogen implantation this characteristic has to be observed with great accuracy because if the injected fuel mass flow is to high the combustion chamber can be overheated. The overpowering of the starting torque presents the most critical phase during the starting sequence.

Due to the fact that modification is based on the main idea to feed always the requested amount on energy in order to archive the same turbine operation characteristics the basic load of the metering unit and therewith of the control unit is to guarantee:

$$\dot{Q}_{Kerosene} = \dot{Q}_{Hydrogen} \Rightarrow \dot{m}_{Kerosne} \cdot \Delta hu_{Kerosene} = \dot{m}_{Hydrogen} \cdot \Delta hu_{Hydrogen}$$

As already mentioned the position of the valve is a dimension of the hydrogen mass flow. So the control loop has to assure always the requested position of the valve for every engine operating condition. Also an over- and undershoot of the valve has to be avoided, because this could even produce an overheating or a flame-out of the combustion chamber. The change from kerosene to hydrogen from a liquid to gaseous medium also includes the possibility of compressive behaviour of the hydrogen. This has to be considered by the design of the control loop's characteristics. Also the hydrogen's reaction rate is even higher than the kerosene's rate. Especially for the ignition of the gas turbine this certainty has an important influence. In order to get a first impression of the operating from hydrogen fuelled gas turbine and the requirements on the metering unit and control loop resulting from this first investigations has been done with a KHD T216 during the first hydrogen investigations at ACUAS years before [6]. Figure 6 shows the difference between the hydrogen and the kerosene ignition of the engine.

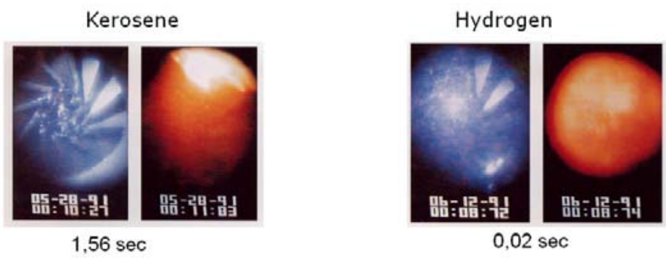


Figure 6: Kerosene versus hydrogen ignition [6]

After 0,02 seconds the ignition of the hydrogen fuel has taken place. This high reaction rate gives also a first indication of the requested velocity of the control loop. All the specified requirements have to be achieved reproducible in order to guarantee a safe operation of the hydrogen fuelled gas turbine.

3.1 Determination of the PID control parameters

The target is it to find out the combination of PID parameter settings which meet the defined requirements best. Figure 7 shows the simplified graphic presentation of the problem.

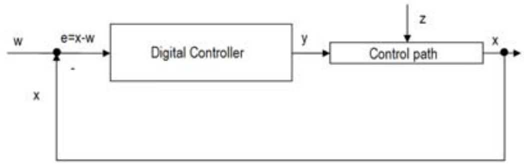


Figure 7: Digital controller

The PID control loop is implemented in the control software of the engine. It accords to the generically PID algorithm.

$$y(t) = K_c e(t) + \frac{K_c}{T_i}\int_0^t e(t)dt + K_c T_d \frac{de(t)}{dt} + y_0$$

$$y(k) = K_c e(k) + \frac{K_c T_A}{T_i}\sum_{i=0}^{k} e(i) + \frac{K_c T_d (e(k) - e(k-1))}{T_A} + y_0$$

$$y(k) = K_p e(k) + K_i \sum_{i=0}^{k} e(i) + K_d (e(k) - e(k-1))$$

Such as in the industrial application usual for the determination of the PID control parameters for the hydrogen metering unit's control loop an empiric approach is chosen in two major steps. First every single PID parameter is evaluated by giving a control value switch by variegating the parameters on the system. Later on with identified PID parameters a functional test is done in order to validate the settings for the complete operating range of gas turbine.

For achieving rapidly the target value without oscillating the first evaluated parameter is the K_P-element of the control loop. All other elements are switched off. For each tested parameter the same procedure is passed through. From the same starting basis (a) a control value switch (2,5a) is given on the system. The different step function responses are shown in figure 8. The values for P elements are given as hexadecimal numeracy.

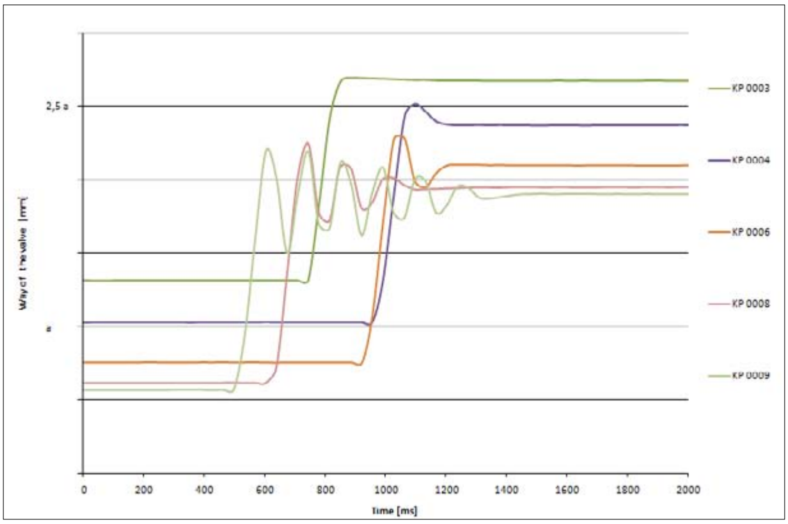


Figure 8: Setting of the K_P-value

The values of the K_P-element will be increased up to the point where the system oscillates. With the value from 0009 the system starts to oscillate. According to Ziegler und Nicholos [7] provides for closed loop control the K_P-value is chosen as 60 % from K_{Pkrit} with K_p = 0006. In order to assure that this fact is also adaptive the following investigations are also done with different K_p-values. The attitude of the system is not as satisfying as with the K_p-value of 0006.

For avoiding a flame-out or an overheating of the combustion chamber caused by an under- or overshooting of the valve the K_D-value has to be adjusted for mimimazing this detrement. Therefore a value switch is given in the system so that valve opens from postion b to postion 1,9375b (Fig. 9). For investitgation the system bahavoir by closing the valve is traversed from 1,9375b to b (Fig. 10). For different K_D-settings this procedure is accomplisehd. The K_I-value is still 0000.

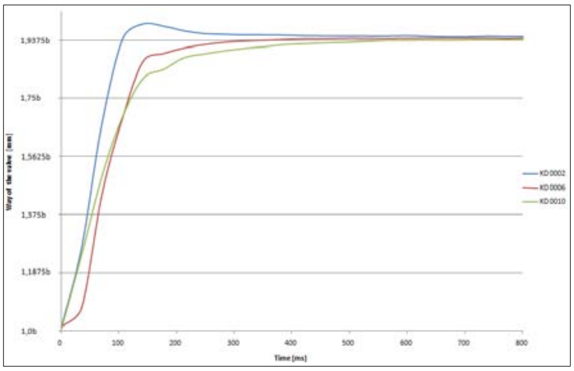


Figure 9: Setting of the K_D-value (acceleration)

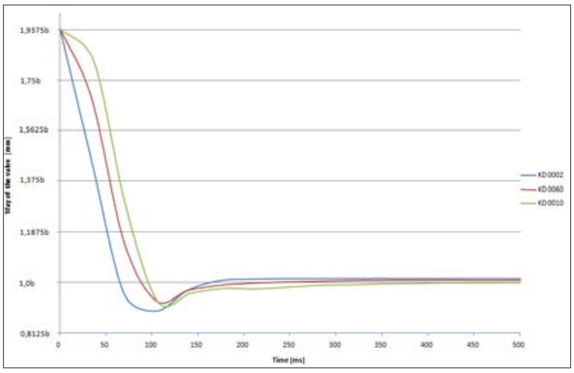
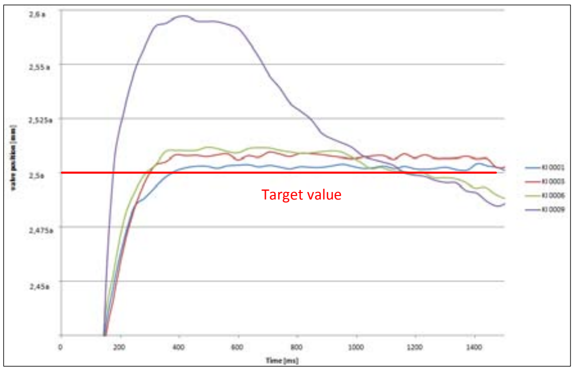


Figure 10: Setting of the K_D-value (deceleration)

For K_D = 0002 a higher overshooting of the valve appears for the opening and closing of the valve. The attitude of K_D= 0006 and K_D= 0010 are quite similar. However the adjustment of the valve is in the K_D= 0006-configuration a little bit faster. For this reason the value is maintained for this configuration. The embedded spring in the hydraulic cylinder causes the undershooting by the movement from higher to lower opening positions (Fig. 10). The fact of the spring is to secure the close of the valve when the hydraulic or control system fails. Because the overshooting of the valve is not so high and it is fast correct by the control loop, it should not have such a great influence on the operation of the turbine.

By setting the K_I-value the offset will be reduced and so a correct metered hydrogen mass flow can be ensured for different operating conditions. The procedure is the same as K_D-value's proceeding. Figure 11 and figure 12 presents the system's behavior for increasing K_I-values. For a better outlook, only the final positions of the valve are illustrated.



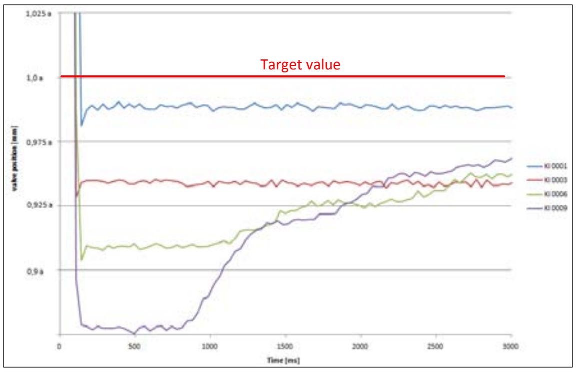


Figure 11: Setting of the K_I-value (acceleration)

Figure 12: Setting of the K_I-value (deceleration)

With the increase of the K_I-value the overshooting of the valve also increases. By minimizing the offset the K_I-value cloud not be adjusted to zero. So the choice of K_I=0001 is a good agreement.

By setting K_P= 0006, K_D= 0006 and K_I= 0001 the closed control loop achieves the designated characteristic for the hydrogen operation of the engine. The valve traverses rapid and precise to the requested position. In addition the settled parameters reduces also an over- and undershooting of the valve. After setting up the PID-element-parameters, the system is tested on functionality. For this reason the valve is traversed several times for the complete operating range of the gas turbine (Fig. 13).

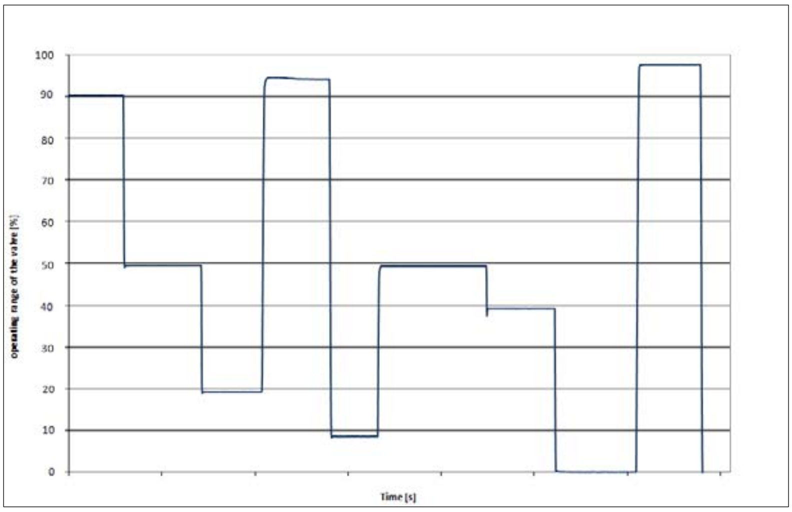


Figure 13: Functionality test

During the functionality test, the valve always traverses precise to the requested positions and so the accuracy of the metering unit for the engine operation is secured. For the opening from zero to maximum range of the valve the systems needs 0,493 seconds. During the normal operation of the engine the valve never does such a step. The anew closing of the valve from the maximum position to zero lasts in 0,246 seconds. This value is important for the emergency shutdown of engine because the fuel supply has to be stopped and to avoid combustion chamber's flame-out during normal gas turbine operation.

4. First starting test and outlook

For testing the starting sequence only the first fuel steps are programmed in the control software. Therefore the engine accelerates after the ignition up to 25%. Figure 14 shows one of the first hydrogen starting tests. The ignition of the engine was audible and has been detected by the engine.

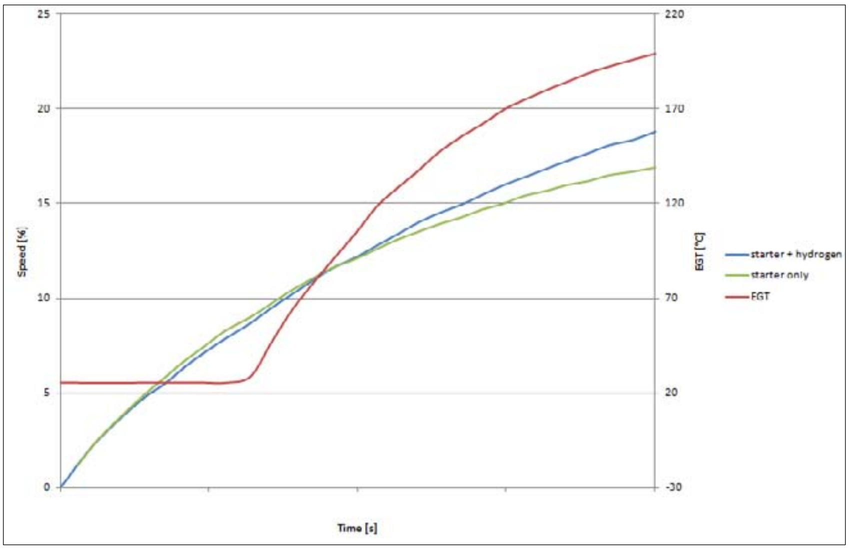


Figure 14: Ignition and acceleration

After acceleration to 7% by the engine's starter the hydrogen valve opens and the hydrogen ignites. Through this the temperature in the chamber increases. In comparison to the "starter only" graph the engine is more accelerated by burning the hydrogen. For overpowering the turbine's starting torque more hydrogen fuel has to be injected in the chamber. As already advised this is the most critical phase during the start sequence because the risk exists to exceed the critical temperatures. Therefore the approach will be done in small steps.

The setting of PID-elements and therewith the correct operation of the metering unit is an important starting basis for the hydrogen operation of the engine. The next milestone will be the full acceleration - from the ignition up the 95% speed - of the hydrogen engine. Later on the two operating conditions of the engine will be tested.

5. References

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