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RE		Restricted to a group specified by the consortium (including the Commission Services)	Yes/ **No**
CO		Confidential, only for partners of the consortium (including the Commission Services)	Yes/ **No**

Contents

1. Abbreviations

CMR: Compact Membrane Reactor

CO: Confidential

D: Deliverable

DEM: Demonstrator

DoA: Description of the Action

DoW: Description of Work

EC: European Commission

EGR: Exhaust Gas Recirculation

EU: European Union

FC: Fuel-Cell

GA: Grant Agreement

ICE: Internal Combustion Engine

IPR Intellectual Property Rights

LCA: Life-Cycle Analysis

M: Month

PC: Project Coordinator

PM: Project Manager

PO: Project Officer

PP: Program Participants

PU: Public

RE: Restricted

RPEMS: Rapid Prototype Engine Management System

SC: Steering Committee

SM: Sales Manager

SME: Small and Medium Enterprises

SQS: Seminal Quality System

T: Task

TCO: Total Cost of Ownership

TM: Technical Manager

WP: Work Package

2. Summary

This document gives detailed information over the critical parameters which must be measured to understand the behavior of each part of the overall system and the physical phenomena behind. Furthermore, a description of the approach to gain all necessary measurement data, also in view of building up an overall process model, is given.

From previous testing activities and investigations, the typical measurement channels for an ICE as well as for a FC are basically known. These channels will also be used within the measurement campaign for the ALL-IN Zero program. The parameters which are measured should give insights for answering the following two questions:

- Understand the physical phenomena of the working process, with a focus on specific characteristics from using H2 as an energy vector.
- Gain sufficient measurement data to set up a system model for further investigations

3. Critical Parameter Identification

3.1 Critical parameter identification for the Compact Membrane Reactor

The Compact Membrane Reactor (CMR) performance will be evaluated regarding catalytic hydrogen generation and electrochemical operation. The validation will be based on the progressive evaluation of the reactor components and cells: (i) CMR working in reaction conditions with individual fuels, (ii) CMR working in reaction conditions with multi-fuel configuration, and (iii) CMR long-term tests to evaluate the stability of the system and thermo-neutral operation.

These tests will enable the evaluation of the hydrogen extraction capacity under working conditions and the effect of different parameters such as temperature, pressure, current, flow rates, and feedstock composition.
Figure 1 shows the Process Flow Scheme (PFS) of a standard CMR for catalytic and electrochemical testing. Mass flow controllers (CG, CL); water containers (WC); evaporators (EV); gas chromatograph (GC); back-pressure regulators; traps; check, relief, and 4-way valves; thermocouples and the planar module reactor (R1) are indicated in the PFS. This reactor is built flexibly and designed to test single electrochemical planar cells or stacks.

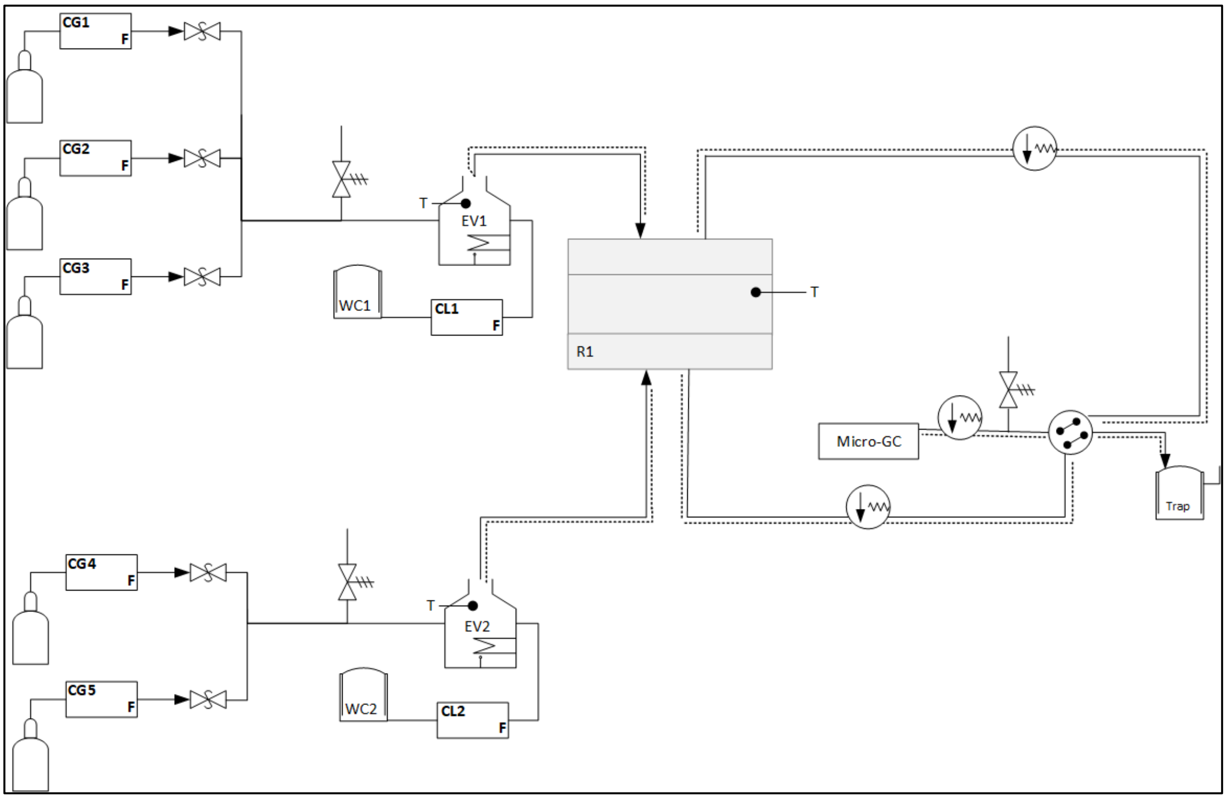


Figure 1: Process Flow Scheme (PFS) for a CMR system.

Table 1 indicates a list of the parameters that will be at least protocolled and monitored to control the CMR system and testing performance.

Table 1: List of the PFS parameters for a CMR system

Channel name	Unit	Description
CG1	ml/min	gas mass flow controller 1
CG2	ml/min	gas mass flow controller 2
CG3	ml/min	gas mass flow controller 3
CG4	ml/min	gas mass flow controller 4
CG5	ml/min	gas mass flow controller 5
CL1	g/min	liquid mass flow controller 1
CL2	g/min	liquid mass flow controller 2
WC1	cm^3	water container (side 1)
WC2	cm^3	water container (side 2)
EV1	ml/min	evaporator (side 1)
EV2	ml/min	evaporator (side 2)
T_EV1	°C	temperature evaporator (side 1)
T_EV2	°C	temperature evaporator (side 2)
R1	-	CMR module
T_R1	°C	temperature CMR module
P_BPR1	bar	pressure back pressure regulator (side 1)
P_BPR2	bar	pressure back pressure regulator (side 2)
GC	a.u.	micro gas chromatograph
iV	V, A	power supply

Table 2 summarizes the range of values to be considered for the reaction tests. During this experiment, hydrogen is produced from different fuels, and subsequently pumped to the H_2 chamber as consequence of the current application. The H_2 production and concentration of the formed products will be analyzed by gas chromatography to determine the Faradaic efficiency and the reaction yield, respectively.

Table 2: Reaction conditions

Parameter	**Values**
Feed flows	1-500 ml/min
Current density	0-2 A/cm^2
Temperature	550-850 ºC
Pressure	1-30 bar

A modelling task will be performed in parallel and having several feedback iterations with the testing activities. CMR validation will provide important information to the final modelling system, enabling to build the models and advance with these tasks. Furthermore, the different model tools will provide on their turn CMR developing and the experimental validation and optimization of the CMR system.

3.2 Critical parameter identification for the H_2 Internal Combustion Engine

All relevant parameters of the engine will be measured and stored for evaluation of the main physical phenomena and energy flows. These data will be the input of a system model (CMR, engine, fuel cell) used for further simulation.

The engine performance, ambient conditions, temperatures, pressures, in-cylinder indication, mass flows, and emissions will be measured.

The installed AVL Puma test bed system provides many norm names to map the engine performance and test conditions. The norm names are a shortcut in English for its measured value (e.g.: T… Temperature, P…Pressure, MF…mass flows, BS…brake specific).

The parameters listed in Table 3 and Table 4 are planned to be measured and protocolled:

Table 3: Overview of main parameters (pressures, temperatures) measured on the engine testbed

Temperatures and pressures Intake side	
T_IA	IntakeAir:TempUpstreamAirFilter
P_IA	IntakeAir:PresUpstreamAirFilter
T_11	IntakeAir:TempDownstrAirFilter#1
P_11	IntakeAir:PresDownstrAirFilter#1
T_21	IntakeAir:TempCompressorOutB#1
P_21	IntakeAir:BoostPressureB#1
T_2_1	IntakeAir:TempDownstreamIC#1
P_2_1	IntakeAir:PresDownstreamIC#1
T_IM	IntakeAir:TempIntakeManifold
P_IM	IntakeAir:PresIntakeManifold
P_MAN	Low pressure indication intake port
Temperatures and pressures Outtake side	
P_EXH	Low pressure indication exhaust port
T_31	EngExh:TempExhManifoldBank#1

P_31	EngExh:PresExhManifoldBank#1
T_41	EngExh:TempUpstrAftertrBank#1
P_41	EngExh:PresUpstreamAftertrBank#1
In Cylinder	
P_MX	MaxCylinderPressure
A_SOC	StartOfCombustionCyl#All
A_SOI	InjTim:StartOfInjectionCyl#All
A_I50	50%MassBurnt:PosATDCCyl#All
A_IGN	Ignition:PosATDCCyl#All
Ambient air condition	
HR_IA	IntakeAir:RelHumidity
HA_IA	IntakeAir:MassFractionWaterVapor
P_0_A	BarometricPressure
T_0	Test Cell Temperature
EGR	
T_EGRHE_I	HeatExchangerEGR:GasTempIn
P_EGRHE_I	HeatExchangerEGR:GasPressIn
T_EGRHE_O	HeatExchangerEGR:GasTempOut
P_EGRHE_O	HeatExchangerEGR:GasPressOut
T_HEEGR_I	HeatExchangerEGR:TempCoolantIn
P_HEEGR_I	HeatExchangerEGR:PressCoolantIn
T_HEEGR_O	HeatExchangerEGR:TempCoolantOut
P_HEEGR_O	HeatExchangerEGR:PressCoolantOut
RT_EGR	ExhaustGasRecirculationRatio
Coolant condition	
T_W_I	Temp:CoolantOuterCircuitEngIn
P_W_I	Pres:CoolantEngIn
T_W_O	Temp:CoolantOuterCircuitEngOut
P_W_O	Pres:CoolantEngOut
T_HEIC_I	Intercooler1:CoolantTempIn
P_HEIC_I	CoolantPressIntercoolerInlet
T_HEIC_O	Intercooler1:CoolantTempOut
P_HEIC_O	CoolantPressIntercoolerOut
H2 condition	
T_FUEL_I	FuelCons:TempFuelSupply
P_FUEL_I	FuelCons:FuelSupplyPressure
T_FUEL_O	FuelCons:TempFuelReturn
P_RAIL	FuelRailPressure
Oil condition	
T_OIL	Temp:OilMainDuctBank#1
P_OIL	Pres:OilMainDuctBank#1

Table 4: Additional parameters measured on engine testbed

Engine performance, exhaust emissions and miscellaneous	
BMEP	MeanEffectivePressure
BS_NOX_EO	EngOut:BrakeSpecificNOXEmission
BS_NOX_EO_S	EngOut:BrakeSpecNOXEmis(REG)
BS_NOX_TP	TailPipe:BrakeSpecificNOXEmiss
BS_NOX_TP_S	TailPipe:BrakeSpecNOXEmis(REG)
BS_O2_EO	EngOut:BrakeSpecificO2Emission
BS_O2_TP	Tailpipe:BrakeSpecificO2Emission
BSFC	BrakeSpecificFuelConsumption
FD_AFST	FuelData:StoechAir/FuelRatio
FD_DESC	FuelTyp:Description
FD_ID	FuelData:UniqueFuelIdentifier
FD_NCALV	FuelData:NetCalorificValue
FD_RHO15	FuelData:DensitityAt15Â°C
H2O_FT1	FTIR:H2O VolumeConc,wet
I_FILE	IndiEquipment:ResultFileName
ID_CURVE	Measurement:CurveID
ID_MEAS	Measurement:MeasurementID
IMEP	IndicatedMeanEffPresCyl#All
LAV	AirExcessRatio(MassFlowMeas)
lav	AirExcessRat(MassFlowMeas)(Onl)
M_FUEL_STR	FuelMassPerStroke
m_fuel_str	FuelMassPerStroke(Online)
md	Engine Torque
MD	AveragedLeverArmTorque
MF_EGR	EGR:MassFlowEGRLine
mf_exh	Online:MassFlowExhaust
MF_EXH	EngOut:MassFlowExhaustWet
mf_fuel	MassFlowFuel(AveragedValue)
MF_FUEL	MassFlowFuel(AnalogOnlineValue)
mf_ia	IntakeAir:MassFlow(Online)
MF_IA	IntakeAir:MassFlowBank#1
MF_NO_EO	EngOut:MassFlowNO
MF_NO_TP	TailPipe:MassFlowNO
MF_NOX_EO	EngOut:MassFlowNOX
MF_NOX_TP	TailPipe:MassFlowNOx
MF_O2_EO	EngOut:MassFlowO2
MF_O2_TP	TailPipe:MassFlowO2
MF_THC_EO	EngOut:MassFlowTHC
MF_THC_TP	TailPipe:MassFlowTHC
N	AveragedEngSpeed

NO_EO	EngOut:NOVolumeConc,wet
NO_FT1	FTIR:NO VolumeConc,wet
NO_TP	TailPipe:NOVolumeConc,wet
NO2_EO	EngOut:NO2 VolumeConc,wet
NO2_FT1	FTIR:NO2 VolumeConc,wet
NO2_TP	TailPipe:NO2 VolumeConc,wet
NOX_EO	EngOut:NOxVolumeConc,wet
NOX_FT1	FTIR:NOX VolumeConc,wet
NOX_TP	TailPipe:NOxVolumeConc,wet
O2_EO	EngOut:O2VolumeConc,dry
O2_FT1	FTIR:O2 VolumeConc,wet
O2_TP	TailPipe:O2VolumeConc,dry
P_CRANKC	Pressure:Crankcase
P_EXPANS	PressureExpansionTank-Air
PED	ActPedalPosition
PWR	AveragedEngPowerOutput
RHO_FUEL	FuelDensitityAtActualTemperature
RHO_IA	DensityIntakeAir
RT_CBAL_EO	EngOut:CBal(MassFlowMeas-Exh)
RT_CBAL_TP	TailPipe:Cbal(MassFlowMeas-Exh)
I_BAT	BatteryAmpere
U_BAT	BatteryVoltage
V_FUEL_STR	FuelVolumePerStroke(StdCond15Â°C)
VEFF	VolEff:TotalWetBank#1
VEFF_IM	VolEff:IntakeManifold
VF_BBY	VolumeFlowBlowBy
H2 in BBY	H2 measurement in Blow-by
H2 sensor	measurement for safety requirements

In addition to the time-based measurement channels, a Cylinder pressure Indication system will be used to gain maximum insights into the combustion characteristics. The Cylinder Indication system consists of a highly dynamic pressure transducer connected to the combustion chamber. In addition, a crank angle sensor, a current clamp for the injector, a current clamp for the ignition coil, and a signal processing unit are part of the Indication system. The Indication system allows for crank-angle-based measurement of the cylinder pressure with a high resolution both in the crank-angle domain and on the pressure level. Measuring crank-angle based gives thereby best insights into the combustion characteristics.

The Indication system will also detect engine Knocking and other combustion anomalies (e.g. Pre-ignition). If such an event is detected, automatic countermeasures within the testbed Automation system should apply, to prevent the engine from being damaged. These countermeasures can produce retardation of ignition timing or in the worst-case a hard shut-down of the engine.

The overview sketch of an engine shown in Figure 2 describes the measurement points and norm names normally used for a multi-cylinder engine. For the single-cylinder engine, the arrangement is slightly different (e.g. external boost pressure instead of turbocharger), but the sketch nevertheless gives a good impression of the logic behind the norm names.

In this project also no exhaust after treatment system will be used.

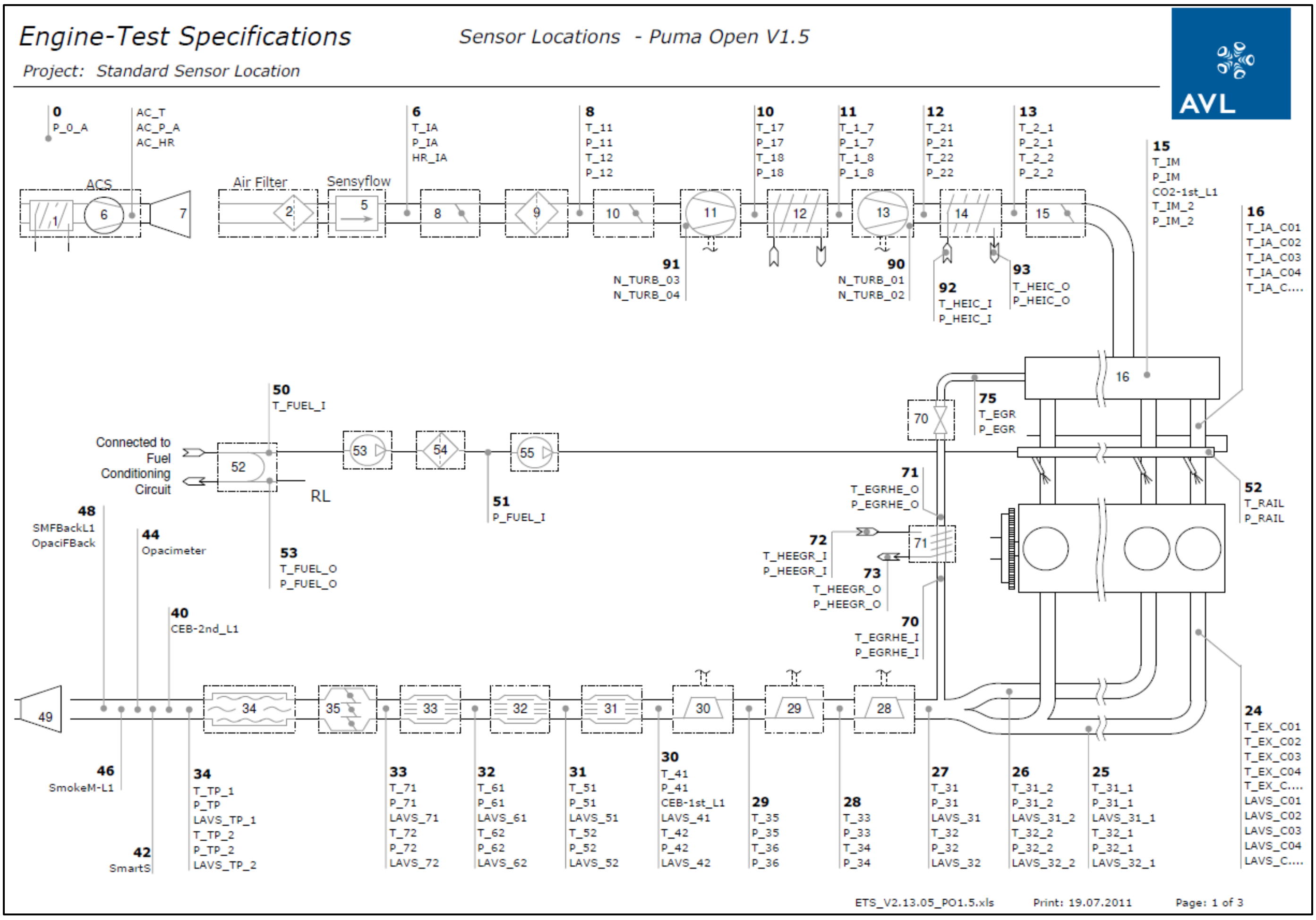
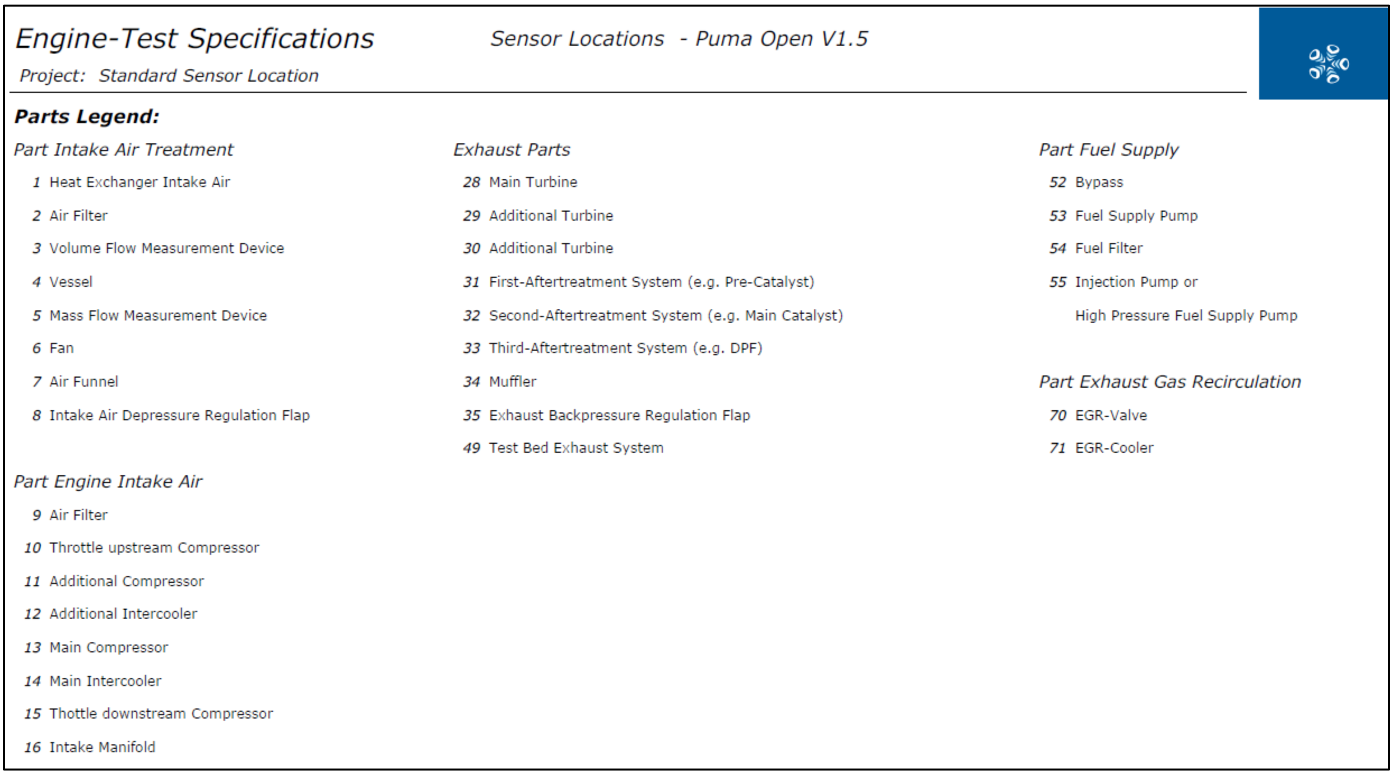


Figure 2: Overview of standard engine measurement channel layout

Figure 3 is connected to the Engine Overview sketch and gives an overview of the various engine parts and the respective number.



Engine-Test Specifications

Sensor Locations - Puma Open V1.5

Project: Standard Sensor Location

Parts Legend:

Part Intake Air Treatment

1 Heat Exchanger Intake Air
2 Air Filter
3 Volume Flow Measurement Device
4 Vessel
5 Mass Flow Measurement Device
6 Fan
7 Air Funnel
8 Intake Air Depressure Regulation Flap

Part Engine Intake Air

9 Air Filter
10 Throttle upstream Compressor
11 Additional Compressor
12 Additional Intercooler
13 Main Compressor
14 Main Intercooler
15 Thottle downstream Compressor
16 Intake Manifold

Exhaust Parts

28 Main Turbine
29 Additional Turbine
30 Additional Turbine
31 First-Aftertreatment System (e.g. Pre-Catalyst)
32 Second-Aftertreatment System (e.g. Main Catalyst)
33 Third-Aftertreatment System (e.g. DPF)
34 Muffler
35 Exhaust Backpressure Regulation Flap
49 Test Bed Exhaust System

Part Fuel Supply

52 Bypass
53 Fuel Supply Pump
54 Fuel Filter
55 Injection Pump or
High Pressure Fuel Supply Pump

Part Exhaust Gas Recirculation

70 EGR-Valve
71 EGR-Cooler

Figure 3: Engine Parts legend for standard engine measurement channel layout

PUMA Open is anyway open also for other nomenclature, specified from the users at UPV. If this will be the case, a list for translating the norm names will be then prepared.

3.3 Critical parameter identification for the Fuel Cell

The fuel cell system (FCS) tests carried out during the project represent a key part of the needed data to implement the desired system model. The obtained output results represent the behavior of one of the possible clean powertrains presented in the project. Furthermore, the input values also have high importance because they should match the possible outputs the CMR can provide.

The FCS performance will be measured in one of the most common ways, by its hydrogen consumption and polarization curve (i-V). Measurement of the voltage also provides the power produced by the FCS and measuring the power of the auxiliary components leads to the net power produced. Other parameters that are highly important for the behavior of the system as ambient conditions (P, T, and RH), stack conditions (P, T, and RH), and mass flows (air and hydrogen), will be measured.

The hydrogen test bed facilities provide a series of data that will be used to analyze the performed tests.

These values are presented in AVL Puma and will be measured as outlined in Table 5:

Table 5: Overview of measurement channels for the Fuel Cell Testbed

Quantity		Channel name	Device	Description
Intake side				
Air circuit				
TAmb	°C	F015C006	FFS-AnalogIn.FFS-AIS-015	IntakeAir: Temp. ambient
Pamb	kPa	F015C008	FFS-AnalogIn.FFS-AIS-015	IntakeAir: Pres. ambient
HumAmb	%	F015C005	FFS-AnalogIn.FFS-AIS-015	Intake Air: RH ambient
TFcIntkInlet	°C	FSA_ContMediumTempSI	MDV_Flowsonix	IntakeAir: Temp. after Air conditioning
PFcIntkInlet	kPa	FSA_ContMediumPressSI	MDV_Flowsonix	IntakeAir: Pres. after Air conditioning
RHFcIntkInlet	%	FSA_HumidityTransducer	MDV_Flowsonix	IntakeAir: RH after Air conditioning
MfFcIntkInlet	g/s	FSA_ContMassFlowSI	MDV_Flowsonix	IntakeAir: mass flow rate
Hydrogen circuit				
PGsmMeasdInlet	kPa	HY_Meas_Curr_InletPressure	MDV_HyTron	IntakeH2: Pres. HyTron Inlet
TGsmMeasd	°C	HY_OPRg_Curr_OutletTemp	MDV_HyTron	IntakeH2: Temp. FCS inlet
PGsmMeasd	kPa	HY_OPRg_Curr_OutletPressure	MDV_HyTron	IntakeH2: Pres. FCS inlet
MfGsmMeasd	g/s	HY_Meas_Curr_MassFlow	MDV_HyTron	IntakeH2: mass flow rate FCS Inlet
Cooling system				
FCE_CoConduct_uScm	µS/cm	CAN7_FCE_CoConduct_uScm	MDV_ConsystCool_200_HT	Coolant: Fluid conductivity
TCoolHtSplyFeed	°C	CS_AirTempSensorTIA350	MDV_ConsystCool_200_HT	Coolant: Inlet temperature
TCoolHtSplyRtrn	°C	CS_AirTempSensorTIA350	MDV_ConsystCool_200_HT	Coolant: Outlet temperature
Battery (pump and comp.)				
ESS2_ACT_I	A	CAN2_ACT_I	E-Storage MV	E-Storage: Actual measured current for auxiliary components
ESS2_ACT_U	V	CAN2_ACT_U	E-Storage MV	E-Storage: Actual measured voltage for auxiliary components
ESS2_ACT_PWR	kW	CAN2_ACT_PWR	E-Storage MV	E-Storage: Actual measured power for auxiliary components
Fuel Cell				

U_act_fuelcell	V	SV_fuelcell_voltage	Nuvera UUT Control	FCS: Actual measured voltage
I_act_fuelcell	A	SV_fuelcell_current	Nuvera UUT Control	FCS: Actual measured current
P_act_fuelcell	kW	SV_fuelcell_power	Nuvera UUT Control	FCS: Actual measured power
ESS1_ACT_I_SLOPE	A/S	CAN1_ACT_I_SLOPE	Nuvera UUT Control	FCS: Actual current slope
FCE_i_StkRmpLimUp_As	A/s	CAN7_FCE_i_StkRmpLimUp_As	Nuvera UUT Control	FCS: Current limit ramp up
FCE_i_StkRmpLimDown_As	A/s	CAN7_FCE_i_StkRmpLimDown_As	Nuvera UUT Control	FCS: Current limit ramp down
FCE_t_ClnAct_C	°C	CAN7_FCE_t_ClnAct_C	Nuvera UUT Control	FC Stack: Actual temperature
FCE_t_ClnSp_C	°C	CAN7_FCE_t_ClnSp_C	Nuvera UUT Control	FC Stack: Set Point temperature

The distribution of the FCS can be better understood when looking at Figure 4. This representation has been taken from the AVL Puma interface of the system.

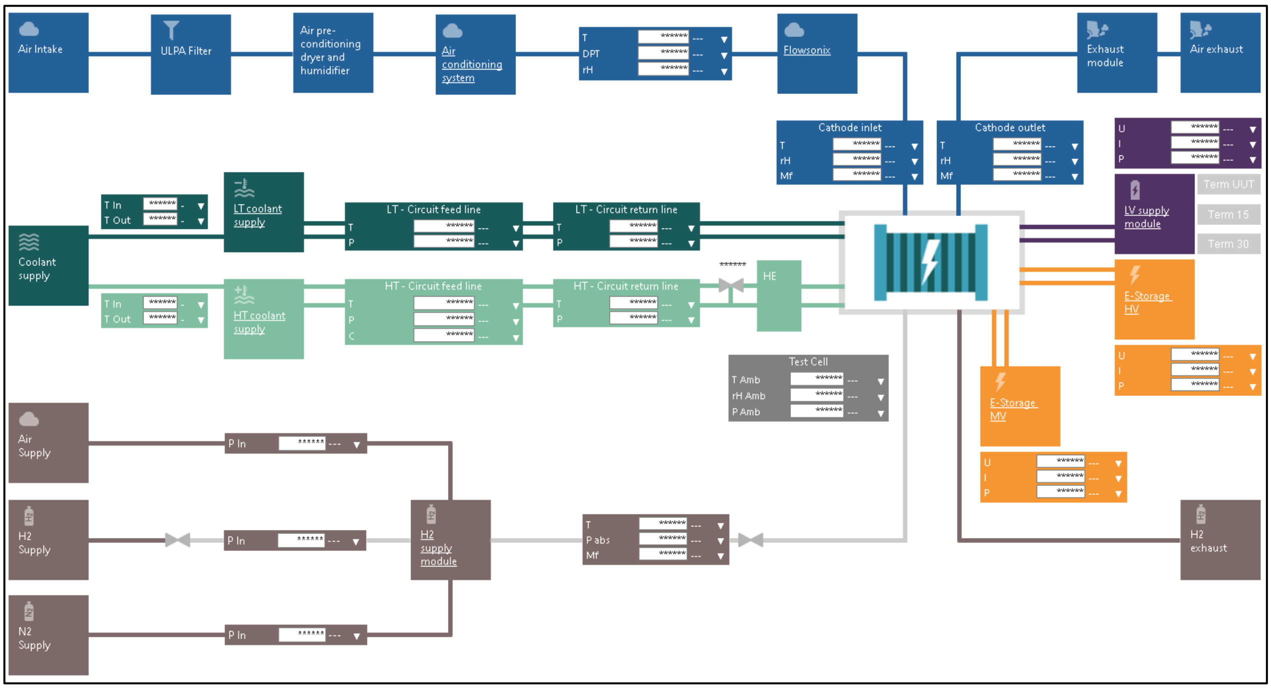


Figure 4: AVL Puma Interface

This scheme shows the different parts of the FCS test bed. The air circuit is represented in blue, in which the Air Take conditions ambient air into the cathode through the flowsonix measurement device. Despite not being sensitized, the cathode exhaust is also represented. The cooling system is represented in green. The lighter tone is used for the glycol system that controls the stack's temperature. The darker part is smaller and consists of coolant that isn't used in the current tests. The hydrogen circuit that conditions into HyTron and then passes to the anode circuit has a brown color. Finally, there are three different power units. In purple, the low-power E-Storage is used to provide current to the ECU that controls the system. The Medium Voltage and High Voltage E-Storages are shown with an orange color. The MV power unit acts as a battery that gives power to the auxiliary components: the compressor and the system's pumps. The HV power unit demands the current of the FCS, acting as the electric motor. Finally, the Unit Under Test (UUT) is connected to all these conditioning facilities and is the Nuvera E-60 Fuel Cell.

4. Test Methodology

4.1 Test methodology for the Compact Membrane Reactor

These tests define and optimize the CMR under the proposed multifuel candidates (NH_3, CH_4, and methanol or ethanol). Firstly, an evaluation of the CMR system using the proposed fuels under a single fuel regime will be carried out to obtain the necessary information regarding the performance of CMR and degradation factors. A series of experiments will be carried out to establish the reference performance of the CMR system under different conditions. The effect of parameters such as temperature (550-750 ºC) and pressure (1-30 bar) will be analyzed for each individual feed mixture. The CMR will also be characterized by means of defined electrochemical parameters, i.e., voltage, area-specific resistance (ASR), and faradaic efficiency. Another activity will be the electrochemical compression evaluation. These results will allow fine-tuning the catalyst composition for a versatile/robust multifuel performance. In parallel, results obtained in FZJ and CSIC concerning CMR characterization, e.g., chemical composition, materials microstructure, and crystalline phase, will be used as an initial reference for the analysis of the degradation mechanism of all CMR components, i.e., electrolyte, electrode, and catalyst. Whilst testing and after reactions, different characterization techniques such as electrochemical impedance spectroscopy (EIS), X-ray Raman scattering (XRS), field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM) will provide information about the materials evolution (sintering, coarsening, poisoning, etc.), to find the connection between the degradation rate observed in the CMR performance and the evolution in materials.

Subsequent multifuel experiments will allow the CMR's operating conditions to be adjusted by testing the desired feed mixtures in fuel-switching operation modes. The input regarding the performance of the CMR in single-fuel conditions will be applied to set the best multi-fuel operation conditions. In this sense, the operation limits will be analyzed and adjusted starting from the information received from the single fuel regime on the CMR degradation mechanisms. These studies will be completed with the characterization of the post-mortem samples.

Finally, long-duration tests will be evaluated to achieve a proof-of-concept for the efficient CMR performance under stable operating conditions, and evaluation of how scaling up the cell impacts the electrocatalytic performances and degradation rates. Long-term experiments will be run under the optimum operating conditions (p, T, flow rate, current). In the experimental protocol, the catalytic parameters will be recorded, and in-situ electrochemical characterization of the samples will be performed at periodic times, i.e., ASR, ohmic, and polarization resistances, to evaluate CMR aging.

4.2 Test methodology for the H_2 Internal Combustion Engine

The focus for the SCE test program is to find the most beneficial hardware combinations and engine combustion settings, which enables the best engine performance with the lowest emission and fuel consumption.

Only stationary operating points will be investigated. In view of the external charging, there is a degree of freedom in setting the operating points. Parameters like lambda (independent from the gas exchange and MFB50%) and EGR rate can be investigated independently.

The choice of hardware will contain two different injection systems like direct injection (DI) with a selection of different blow caps and port fuel injection (PFI), and two different cylinder heads (tumble and swirl).
Starting with the tumble cylinder and PFI injector several selected load points, e.g.:

- 1900rpm and 500Nm
- 1200rpm and maximum torque
- 1200rpm and 800Nm
- 930rpm and 515Nm

would be tested without and with different EGR rates in a combination of setting different lambda levels and injection and ignition timings for targeting the best engine performance.
The 1200rpm 800Nm load point is a typical road load point for an engine in this engine class.
After the definition of the setting for the operating points, the test series will continue with the DI injector investigation. If it is possible to get a swirl cylinder head, the test with PFI would be repeated with the same target of finding the optimum setting of combustion parameters. Afterward, a short test series with the DI injector will be performed to get a comparison to the PFI injector.
Starting with a small number of operating points for selecting the most promising hardware regarding best engine performance and exhaust emissions, a rough calibration of the entire engine map with the best hardware combination can be done.

Sensors that AVL will send together with the engine:

- High-pressure transducer: AVL GH14DK
- Two low-pressure transducers: AVL GU21C (needs external cooling, will not be provided from AVL)
- Lambda sensor
- Camshaft sensors
- Crankshaft sensors

The base engine will be delivered with the above-listed sensors and the following hardware:

- DI injectors
- PFI injectors
- Blow caps
- H2 rail
- Intake manifold
- Exhaust manifold
- RPEMS and wiring harness

- Cylinder head gasket
- Spark plug
- Ignition coil

UPV will provide and build up all for testing necessary hardware like:

- Test bed and it's engine control system
- Inlet and outlet plenum
- EGR valve
- EGR cooler
- Pipes
- Exhaust flap
- H2 sensors for safety operation
- All measurement devices
- External boost pressure (Roots blower…)
- H_2 supply

4.3 Test methodology for the Fuel Cell

The goal of the tests that will be carried out through this project is to find the most appropriate operating conditions to operate with the FCS efficiently. The performance definition of the desired operation is defined in terms of hydrogen consumption, costs (TCO), emissions (LCA), and durability of the whole system. The presented test plan aims to obtain significant data to optimize these characteristics.

Obtaining an efficient operation for the FCS means understanding its behavior in real operating conditions. Therefore, the performed tests can be divided into 3 different parts. Firstly, a stationary set of operating conditions will be considered to characterize the steady-state behavior. Then, some transient tests will allow the characterization in dynamic conditions. Finally, current profiles representative of driving cycle conditions will be imposed to evaluate the FCS performance in realistic and standardized driving cycles.

The owned test bed allows a high level of flexibility to try different operating conditions. In the present project, the FCS represents one of the main possible propulsive systems inside a vehicle, producing power after hydrogen fuel generation. The intake of any FCS is composed of air and hydrogen flows. In this case, the inlet conditions (pressure and temperature of each fluid) gain importance because the system is implemented inside the vehicle. The tests will be carried out for different hydrogen and air conditions to understand the differences it produces in its behavior. Afterward, these results will ease the coupling of the FCS with the CMR.

Another important parameter whose effect will be carefully studied during the tests is the air intake relative humidity. This value is important because the fuel cell membrane needs constant hydration. Dry air flows inside the system may lead to high degradation levels and a conductivity reduction of the membrane. However, an excess of humidity may also negatively affect the FC and lead to flooding of the electrode and an increase in concentration losses [1].

The ConsystCool AVL facility controls the coolant pumped into the system and its temperature. This facility and the appropriately designed PID controller let the test bed user establish the stack temperature that should be maintained during the operation. Therefore, once the intake conditions have been varied and a representative or optimum operating point has been decided, a set of stack temperatures (always under the stack limit of 80°C) will also be tested to understand its effect on the system.

The outlet circuits of the system are also very significant for its performance evaluation. In addition, it is not possible to measure the compressor or cooling pump power separately. Thus, the measurable parameters that will be used to understand the system's behavior are the stack current, voltage and system's power, the auxiliary components' power, and the mass flow intakes.

Once the previously mentioned conditions are analyzed for the steady-state case, the user will have a rough idea of the behavior of the FCS and its optimal operating conditions. Then, the transient characterization will be carried out by changing the current profile demanded by the FCS.

The performance of the FCS under dynamic conditions will be characterized by three main tests in which three different current change rates over time will be tested 2 A/s, 4 A/s, and 5 A/s to increase current and 2 A/s, 5 A/s, and 10 A/s to decrease it. These tests are:

1. Increasing and decreasing ramps using larger steps than in the polarization curve protocol. These large steps intend to simulate a steady-state behavior so that it can be further analyzed and separated from the current change period [2].
2. High current steps testing. These tests have high importance in understanding the behavior under power peaks. They will be carried out under different levels of stabilization time to analyze the transient behavior with further detail. The way the system behaves under these conditions may be representative of how it might behave under some real driving cycle conditions.
3. Random ramp set. This last protocol represents a mix of the previously presented trials [3].

After these tests, the FCS will also be subjected to real driving cycle conditions representative of a heavy-duty vehicle operation. For this purpose, two standardized HDDT (Heavy-Duty Diesel Truck) driving profiles are selected [4], the cruise and transient segments. A virtual vehicle integrating an energy management strategy and other components of the powertrain such as the battery and the electric motor will generate the load profiles for the standardized and realistic driving conditions based on TENT routes [5].

Finally, different polarization curves will be measured and monitored during the defined tests. This protocol will allow the measurement of the voltage standard deviation to understand any hysteresis produced by the transient testing and the degradation mechanisms in the stack.

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