A novel approach to highly integrated thermal management rig and facility for vehicle applications

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Abstract: vehicle system requires the use of hardware/software/control strategy to provide cooling/heating of the cabin, powertrain system and electrical devices. All functions have to be delivered on cost for the customer but also on weight and efficiency to lower energy consumptions and maintain human comfort at all ambient temperature. Thermal Energy Management (TEM) optimisation is critical as ambient temperature variation proves to have a large effect on vehicle energy consumptions for the different types of propulsion systems [1].

Thermofluid system based on highly integrated coolant, refrigerant and air subsystem which are highly integrated require deep level development. They are responsible for enabling energy transfer between sub system to limit heat waste and maximize energy efficiency

This is usually performed using Computational Aided Engineering (CAE) methods during development and validated on rigs and prototype. While component and subsystem rigs are essentials in validation steps, they cannot enable super system level validation. Prototypes on the other hand do but can lack robustness, maturity and their operational time requirement might not be compatible with engineering development cycle and certifications timing. A thermofluid system rig, based on Hardware in the Loop (HiL), is the key to make the link between these two validation stages of the components but also of the system while reducing the development time and accelerate time-to-market.

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This paper introduces a novel approach of a highly integrated HiL rig which combines the entire thermofluid super system – under – test (SUT) of the vehicle. The faster than real time digital twin approach enables eliminating all propulsion systems with thermal emulators designed to replicate the heating & cooling into the thermal system plant. Multiple distributed controllers are also integrated part of this rig, within the scope of the SUT. A novel approach of digital twin use for front end airflow emulation is also introduced in this complex thermo-fluid rig. This rig enables sign off entire thermofluid system hardware & its associated control systems with time to test reduced by up to 94%.

1 Thermofluid system within vehicle applications

Within vehicles, thermofluid systems are comprised of the coolant, refrigerant and HVAC sub system. They are supported by LV/HV architectures, and also by the mechanical engine duty in some case like with engine driven coolant pumps. It has the duty of transferring energy across the different vehicle subsystems and it is responsible for cooling and heating the vehicle cabin, the powertrain sub system and diverse electronic components.

Thermofluid system approach enables combining the different individual loops to optimize the energy transfer within the vehicle but also with the surrounding ambient. Such complexity requires the use of highly intelligent control and calibration. This is key to fulfil thermal comfort within the cabin but also to maximize powertrain efficiency leading to improved range and lower emissions.

The current automotive industry shows a wide range of thermal strategies and methods to provide heating and cooling to the thermofluid system. Coolant heating can be achieved through the High Voltage Coolant Heater (HVCH), through the high voltage compressor or by harvesting powertrain wasted energy. The cabin heating can be performed by harvesting Internal Combustion Engine (ICE), using an electric cabin heater, a cabin heater core combined with a high voltage coolant heater or ambient air heat recovery system (heat pump).

While the system performance is a key aspect for choosing the best system, the weight, complexity and cost need to be balanced. Another aspect is the ambient range expected on the market where the vehicle is sold: while some vehicles are dedicated to specific market with more favourable environmental condition, some are sold to market with more extreme weather (i.e cold and/or hot). This will affect the energy consumption [1]. The jaguar I-Pace released in 2018 relies for example on HVCH to heat the coolant system, a coolant heater core to transfer the coolant heat to the cabin through the Heating, Ventilation, and Air Conditioning system (HVAC), two dedicated Low Temperature Radiators (LTR) for the battery and the propulsion system, a refrigerant arrangement with a high voltage compressor and the associated components that enables a heat pump mode. This mode enables the harvest of heat from low ambient temperature and to transmit it to the cabin in order to reduce the energy consumption while heating the cabin. In cold ambient condition, this helps maximizing the range.

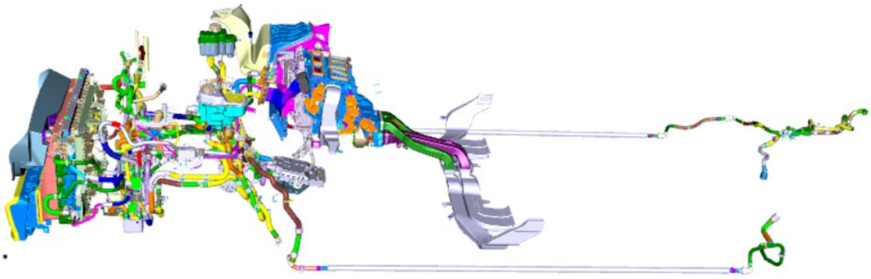

Figure 1: Jaguar I-Pace thermofluid system

As shown in the figure 1, we associate to the system components dedicated to deliver the airflow to the different air to coolant and air to refrigerant heat exchangers such as the cooling fan, the ducting, the grille shutters and the related ducting.

In a recent study that compiled Jaguar I-Pace customer data [1], it was shown that despite using a heat pump system, the average energy consumption at 0deg C ambient is 50% higher than at 20deg C. The energy consumption relation to the ambient temperature for this vehicle is shown in the figure 2. This low and high temperature drives for additional load on the TEM system. Optimising the hardware, control and calibration is therefore key to lower energy consumption and maximize the EV range.

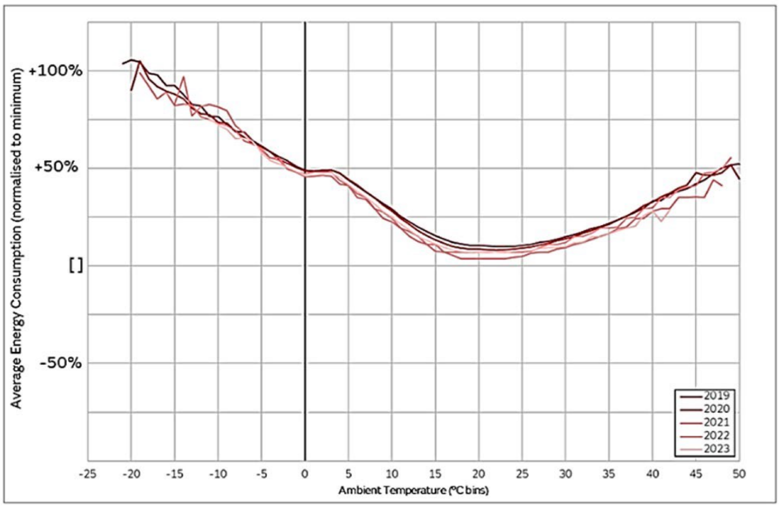

Figure 2: Energy usage as a function of the ambient temperature on the Jaguar I-Pace [1]

2 V system and development cycle

Typical automotive development follows the V model of system engineering. It is split in two main steps. The left branch relates to the requirement/attribute target definition followed by designing stages of the systems, sub-systems and components. These stages rely mostly on CAE development that can be performed using 1d and 3d modelling.

During the second stage, the aim is to verify and validate the components, sub-systems, systems and finally the attributes performance. While components performance and sub-systems can be tested on physical rigs, the industry relies mostly on testing full vehicle with different level of component maturities. This can prove challenging when relying on in-market testing and the test facilities availabilities.

Beside hardware testing, another important part of the testing relates to the software, control and calibration. This is critical to ensure the system functions are delivered efficiently and robustly. For the example of the thermofluid, control and calibration are important with regards to the arbitration of the cabin and powertrain heating/cooling delivery. Although the system might be sized based on the thermal performance load cases with high loads and extreme temperatures, the system needs to deliver the required output for the lowest amount of energy to optimize the powertrain and overall vehicle efficiency.

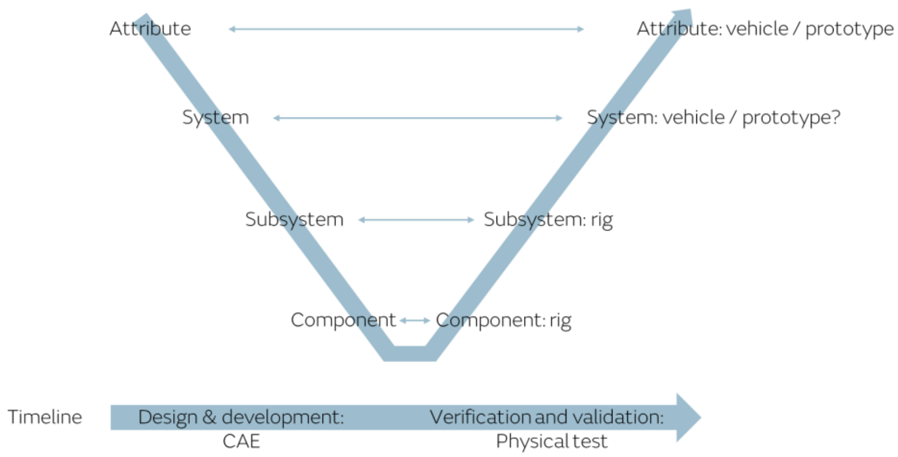

Figure 3: V shape of engineering

One of the downfalls of relying on prototype vehicle testing for system validation and verification can be the maturity level of the vehicle, some of the lengthy time required by specific load case and sometimes the reliability of the properties. Changing critical components to update a vehicle can lead to significant downtime in the development process due to part retrofitting periods, the possible re-instrumentation requirements and the associated challenges. For specific drive cycles, preconditioning, and testing can take up to thirty six hours per drive cycle.

For all these reasons, having the possibility to test thermofluid system on a dedicated HIL bench test apparatus is critical. The use of such physical approach is an area of development for automotive applications [2][3][4]. The following section introduces the newly developed highly integrated rig.

3 New Hardware in the Loop (HiL) test rig approach

The so called “thermofluid level 5 rig” has been developed with the aim of enabling the full thermofluid system testing for a wide range of environmental conditions on steady state and transient load cases. It intends at testing all the refrigerant, HVAC, coolant and air subsystem so that it allows the testing of the controller and fluids interactions as it is shown on the figure 1.

To allow flexibility and to remove sensitivity to part, a number of sub-systems and components are emulated: this includes the heat and cold sinks such as the engine, battery, the front and rear Electric Drive Units (EDU), the electrical components that require heating/cooling and the cabin. This is possible by making the bench working alongside vehicle 1d models that have been developed in the prior phase of the design. Such models need to be real time capable.

The commissioned test bench is composed of an environmental chamber that contains its own conditioning unit. It is capable of controlling the ambient condition within -20 to 50°C. The chamber is sized so it can contain the vehicle labcar that holds the vehicle thermofluid unit. The Heat Exchangers (HX) can be mounted in the vehicle line position on the labcar or on a dedicated front end unit that is designed to replicate real airflow distribution as seen by the vehicle on the road. This apparatus is critical as airflow distributions have an impact on the performance of the air to coolant or air to refrigerant as shown in [5][6][7]. The delivery of the air to the front end unit is performed by the main air handling unit. It is capable of delivering air mass flow representative a high speed load case to the cooling pack for a range of temperature of -20 °C up to 75 °C and an adjustable relative humidity between 10 % and 90 %. Similarly, airflow conditioning to the front and rear HVAC units are handled by separate Air Handling Unit (AHU) and are capable of replicating recirculation mode or fresh inlet from the surrounding environment. The labcar is instrumented with all the required sensors. This includes current and voltage sensors to capture energy usage over cycles, temperature sensors on the different fluid networks but also refrigerant and coolant flow rate sensors. The rig is capable of supporting Low and High voltage components like electrical compressors, but it can also be associated with a dedicated bench that enables the use of mechanical compressors that are used in ICE and hybrid vehicles.

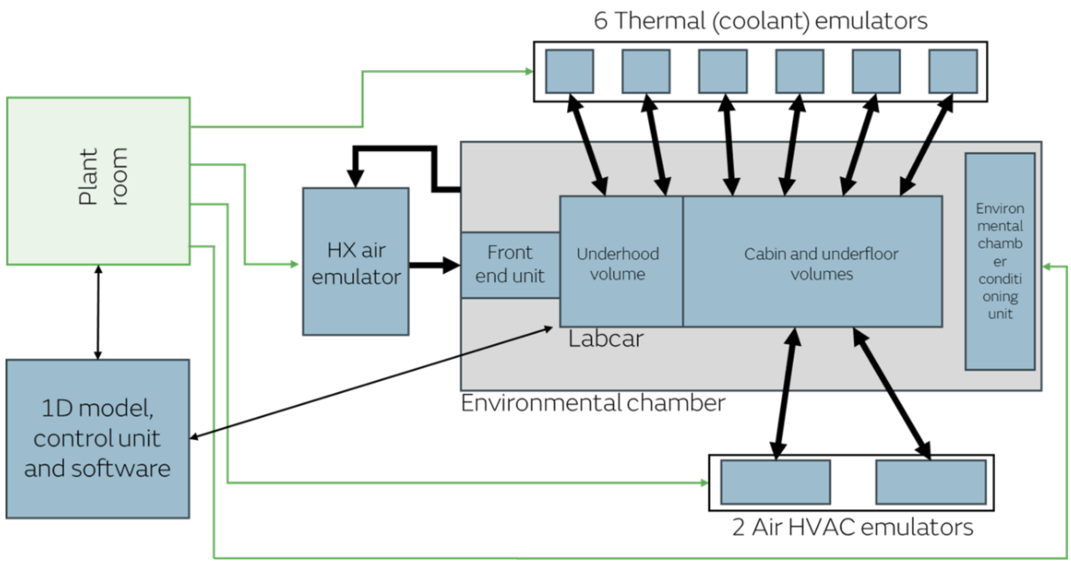

Figure 4: Schematic of the thermofluid level 5 rig

The vehicle components that are handled by the 1d model and emulated on the rig with heating and cooling loads are handled by six individual coolant emulators. They can be used to replicate the components interacting with the fluid network that are not on the labcar like the powertrain units. These coolant emulators have the capability to be controlled through heating or cooling loads (from -12kW to +20kW each) or based on temperature profiles. If individual emulator heat loads are not sufficient, they can also be connected and run in series to increase the cooling or heat delivered to the labcar. Adjustable pressure valves are used when connected to the labcar to be representative with the vehicle expected coolant loop characteristics and pipe connections to the labcar are designed to replicate the total vehicle coolant volume.

Figure 5: -1: Coolant emulators -2: Plant room -3: Coolant emulators secondary -4: Environmental chamber

The labcar contains some of the vehicle ECUs while some can be modelled within the 1d model that is used on the rig. It is made of two volumes to enable temperature control: the larger one contains the components that sit in the cabin volume, and the smaller one represents the underhood volume. The underhood side is connected to the front end unit. This unit is designed to enable the emulation of the airflow distribution onto the cooling pack and represents a novelty.

Figure 6: Labcar

4 Novel approach to air to HX emulation within a rig

One of the key aspects to this rig is the particular attention brought to the air emulated to the front end unit containing the vehicle cooling pack. This system is made of the main air handling unit, the pipe connecting it to the front end unit, the front end unit, the labcar and the return pipe. As shown on the figure 7, it starts from the main AHU which is controlled to provide a specific mass flow and temperature. The air is delivered to the front end unit through some piping into the environmental chamber. This unit contains the vehicle cooling pack and is then connected to the labcar underhood volume.

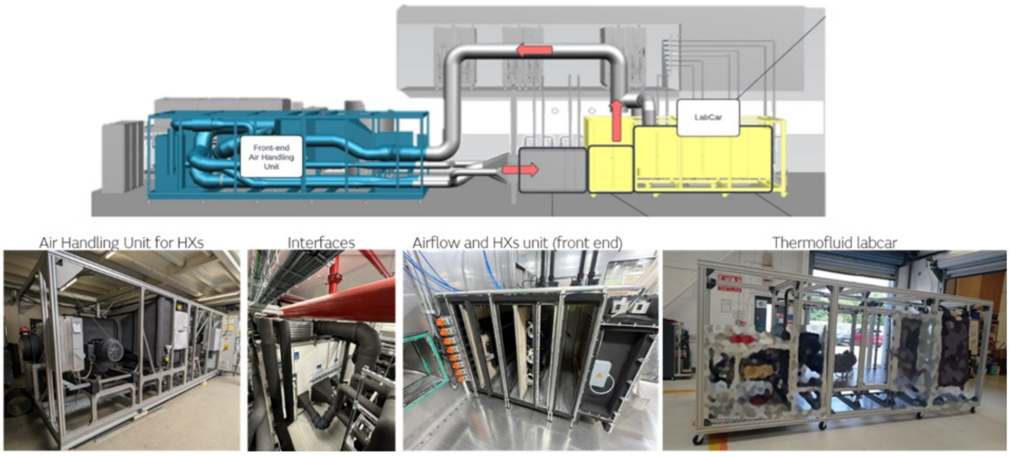

Figure 7: The main AHU flow path

On a typical drive cycle, the main air handling unit is capable of following the transient air mass flow trace from specific drive cycle while taking into account the dynamic movement of the active air system such the active grille shutter and the electric cooling fan. The figure 8 represents a typical Thermal Energy Management drive cycle and the air mass flow input to the rig and its response.

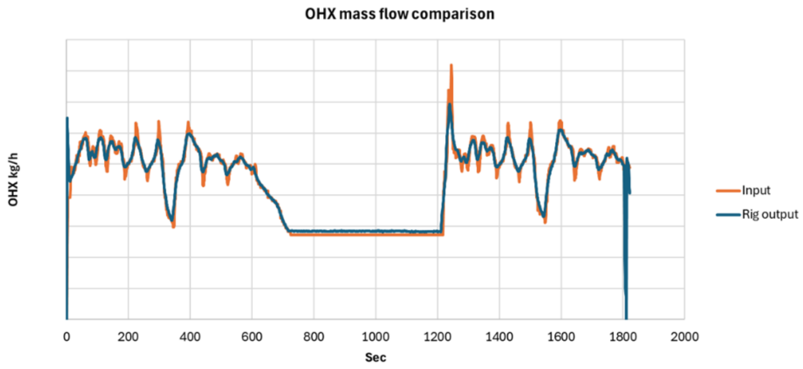

Figure 8: transient air mass flow trace input and output

Beside the total air mass flow, the airflow distribution influences the amount of heat transfer exchanged between the air and the coolant/refrigerant heat exchanger. This is a function of the front end design of the vehicle, the active grille shutter position and the fan power and it is a well-documented phenomenon. [6] shows the impact of airflow blockage onto the refrigerant performance and energy usage. [5] [7] shows that for a typical coolant to air heat exchanger with a uniformity index of 0.6, 10%, or even 20% to 30% of heat rejection decrease can be expected from a perfect uniform airflow performance. This loss of heat transfer performance needs to balance with additional airflow which either means additional fan power or increase active grille shutter opening. Both methods are equivalent to an increase of energy consumption of the thermal system. The following figure shows typical air mass flow distribution onto the HX inlet faces for different vehicle speeds.

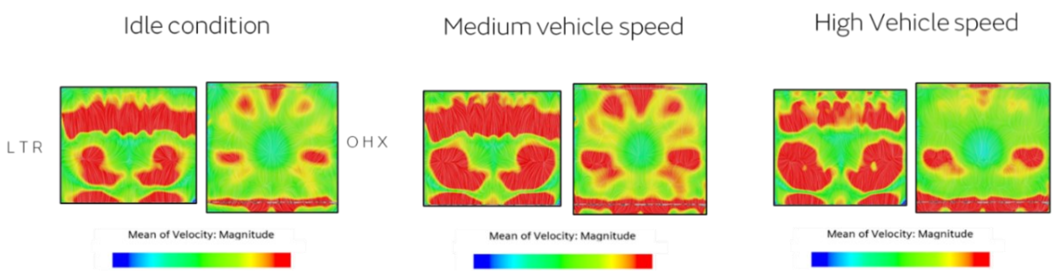

Figure 9: Air velocity distribution for different vehicle speeds

One of the requirements of the test bench is to enable the replication of this airflow condition on the test bench within the front end unit. The front end unit within the environmental chamber is composed of four volumes: two to emulate the airflow distribution and two to integrate the vehicle cooling hardware, as shown on the figure 10. The first airflow distribution emulator system is the most upstream section and is composed of eight horizontal individually actuated vanes which influences the airflow distribution on the height axis. Downstream, the dynamically actuated vehicle vanes are fitted and are controlled through either the vehicle ECU or the vehicle model. It is followed by a static blockage that adds an element of control to the distribution ahead of the vehicle cooling pack.

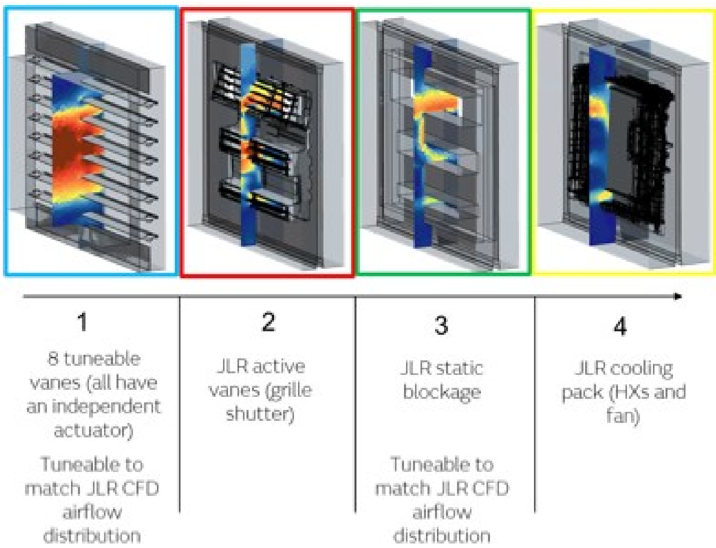

Figure 10: Front end unit description

The tuning of the rig is performed through the use of a correlated CFD model of the airflow system of the bench. It can be used to investigate the airflow distribution within the rig and be used to tune the test bench, so it provides the same airflow as expected on the vehicle. The test rig CFD model includes the air handling unit inlet to the front end unit up to the labcar entry.

The whole thermal vehicle CFD model output is used to describe the airflow distribution for different active system configurations and vehicle speed range. A DoE is then performed using the correlated test bench CFD model which enables the selection of the best blockage which can then be manufactured and integrated onto the front end unit.

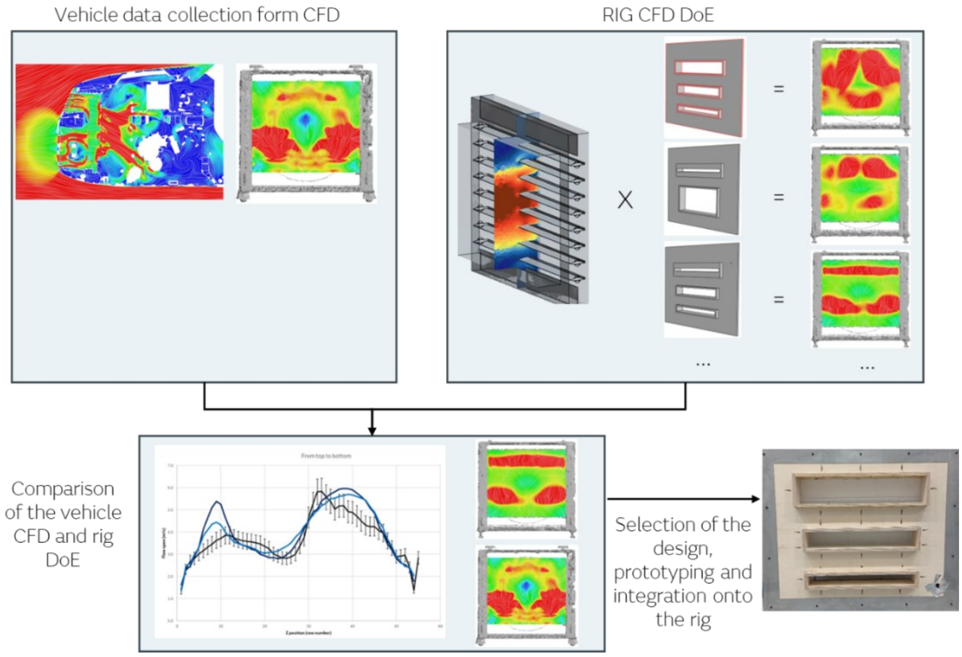

Figure 11: Airflow distribution mapping from vehicle CFD to the front end unit

The different sections of the front end unit can be integrated through a system of sliders to easily access the components while insuring it is possible to connect them to the low or high voltage, coolant and refrigerant system while also maintaining a good seal one the components are in place in the unit.

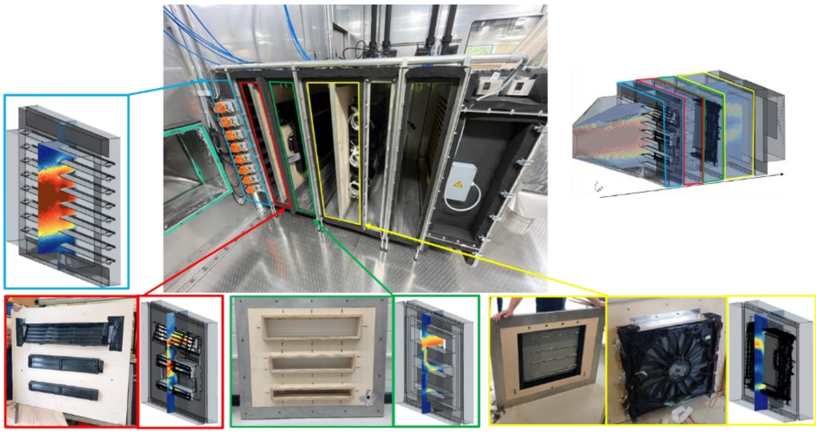

Figure 12: Front end unit and its CFD representation

5 Development and test benefits

The use of the thermofluid rig enables a faster approach to system testing and validation ahead of classical vehicle testing. This supports the Thermal Energy Management performance measurement and control optimisation while allowing the flexibility to easily replace specific hardware and save development time. Full vehicle testing also require extended preconditioning period which can be minimize on the rig thanks to the fast dynamic control of the plant room. Typically, for EPA and WLTP physical testing, this pre-test soak and conditioning can last up to thirty six hours while they can be performed in under one hour on the rig. This is similar with OEM specific and other real world driving replicated drive cycle which might have to be performed a number of times over the thermal system development and validation.

Beside this, although it could take days for replacing physical components on a vehicle prototype leading to extended property downtime, this can be performed quickly on the associated propulsion 1d model.

Based on these typical examples, we believe such rig enables sign off entire thermofluid system hardware & its associated control systems with time to test reduced by up to 94% compared to traditional method

6 Conclusions

The aim of this paper was to demonstrate the application and benefits of a HiL rig for thermofluid applications This is possible by eliminating all propulsion system with a combination of air and coolant emulators. This includes the overall main specifications, operations method and benefits for the aim of validating and investigating the performance of physical hardware and the associated control and calibration.

It also includes a novel method to emulate airflow conditions on the inlet of the heat exchangers as per the expected vehicle condition through the use of vehicle and test bench CFD. This enables adding the air system for the overall thermal energy management system approach on a physical test rig.

This paper introduces a novel approach of a highly integrated HiL rig which combines the entire thermofluid super system – under – test (SUT) of the vehicle. The faster than real time digital twin approach enables eliminating all propulsion systems with thermal emulators designed to replicate the heating & cooling into the thermal system plant. Multiple distributed controllers are also integrated part of this rig, within the scope of the SUT. A novel approach of digital twin use for front end airflow emulation is also introduced in this complex thermo-fluid rig. This rig enables sign off entire thermofluid system hardware & its associated control systems with time to test reduced by up to 94%.

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8 Reference list

[1] Dutta, N., Evans, D., and Sapte, A., “A Percipient Analysis of Jaguar I-PACE Electric Vehicle Energy Consumption Using Big Data Analytics,” SAE Technical Paper 2024-01-2879, 2024, doi:10.4271/2024-01-2879.

[2] Leighton, Daniel. Combined Fluid Loop Thermal Management for Electric Drive Vehicle Range Improvement, No. 2015-01-01709. SAE Technical Paper, 2015.

[3] Chowdhury, S., Leitzel, L., Zima, M., Santacesaria, M. et al., “Total Thermal Management of Battery Electric Vehicles (BEVs),”SAE Technical Paper 2018-37-0026, 2018, doi:10.4271/2018-37-0026.

[4] Bires, M,. “Driving Tomorrow’s Vehicles: AVL’S Software Thermal Management Developing Process to Ensure Calibration on System Level”, No. 24TMSS_0064. TMSS, 2024.

[5] Baskar, S. and Prince Arockia Doss, S., “Investigation on Underhood Airflow Management - Effect of Airflow Statistics,”SAE Technical Paper 2018-28-0024, 2018, doi:10.4271/2018-28-0024.

[6] Kumar Reddy, J., Deopa, S., Sharma, A., and Aggarwal, P., "Impact of Condenser Opening Area on A/C Performance of the Automotive HVAC System," SAE Technical Paper 2015-01-0368, 2015, doi:10.4271/2015-01-0368.

[7] Johnson, A,. Vaddiraju, S., and Solomon, J., “Impact of Airflow Non-Uniformity on Heat Exchanger Performance”, GT Conference 2020, 2020.