



ASHOK LEYLAND

Koi Manzil Door Nahin

Thermal Management of a Fuel Cell Electric Truck

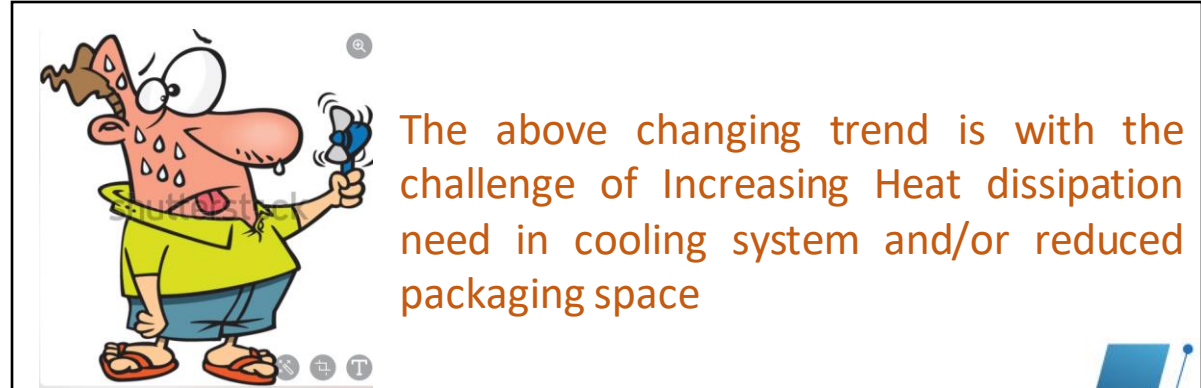
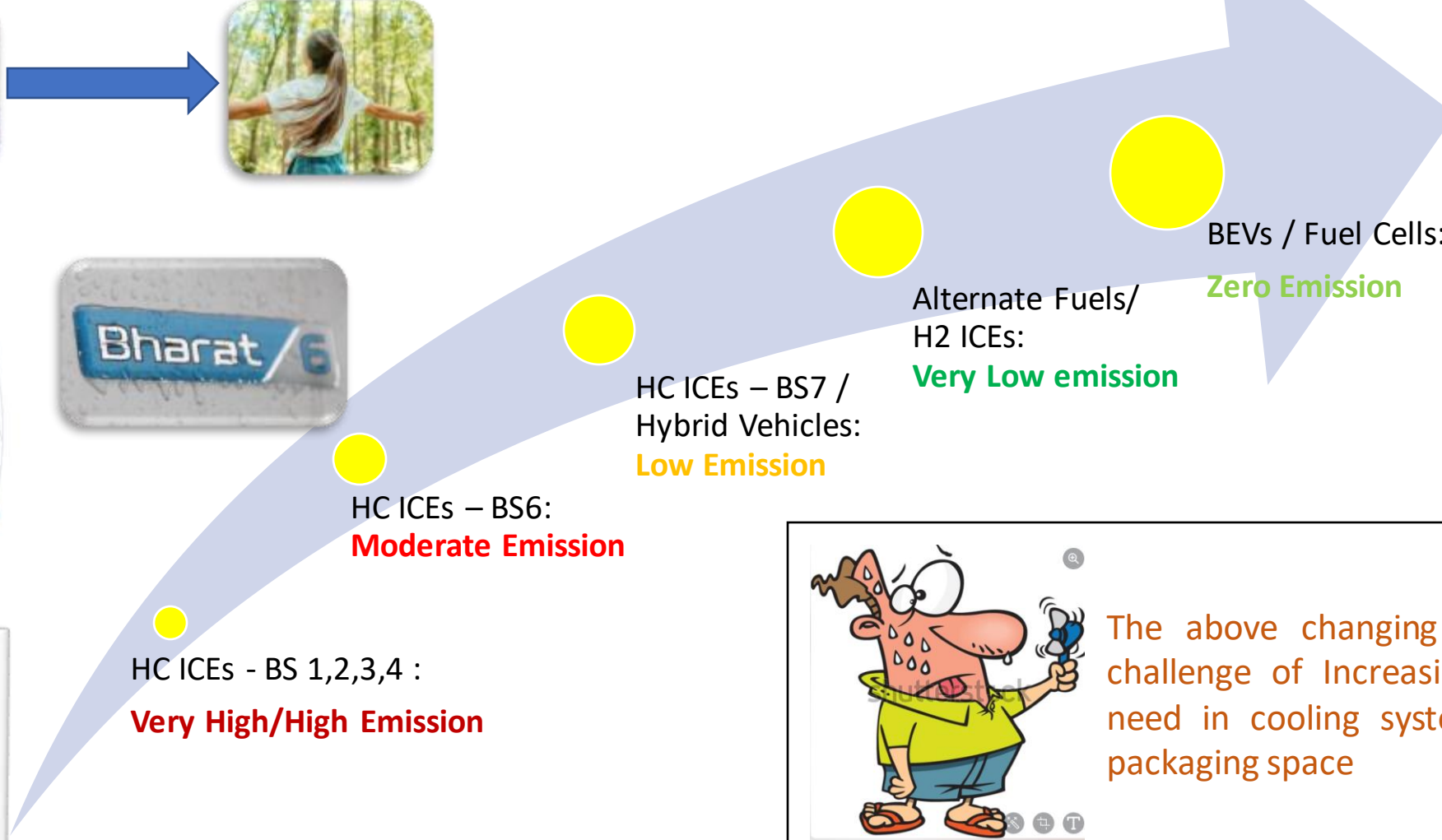
Kiran N

Ashok Leyland Ltd. India



HINDUJA GROUP

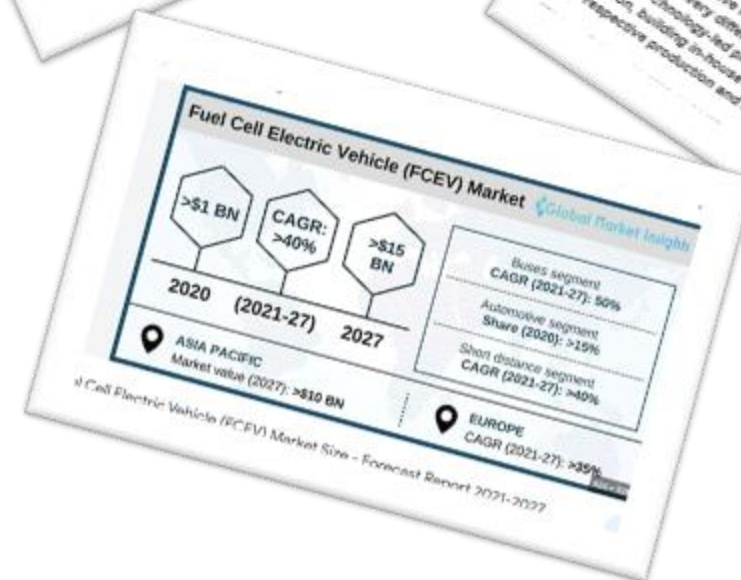
Road Map to achieve Net Zero



Global Trend towards Reduced Emissions



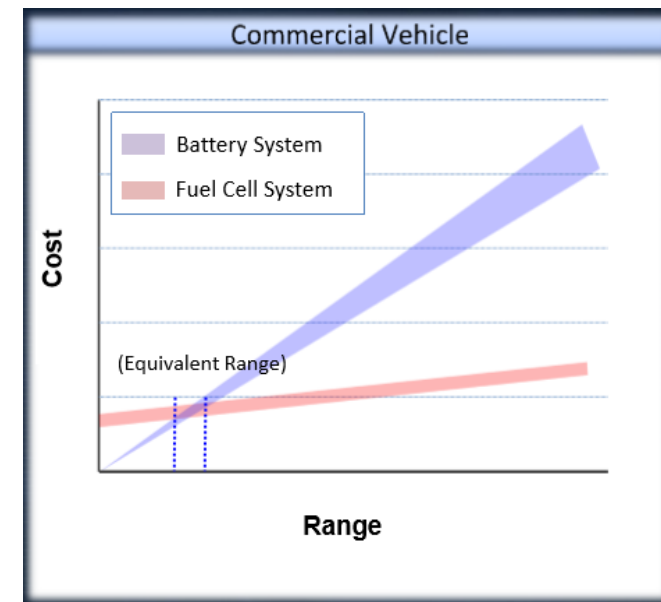
- To achieve net zero, the whole world shifting the strategies from Hydro Carbon Internal Combustion Engines to alternate fueling methods.
- Strong Drive from Regulatory authorities and Incentives from Government to reduce the emission and adopt alternate Fuel technologies
- Many Global Automotive OEMs already declared strategies to end conventional ICE production and moving towards Electric Vehicles / Fuel Cells/ Alternate Fuels.



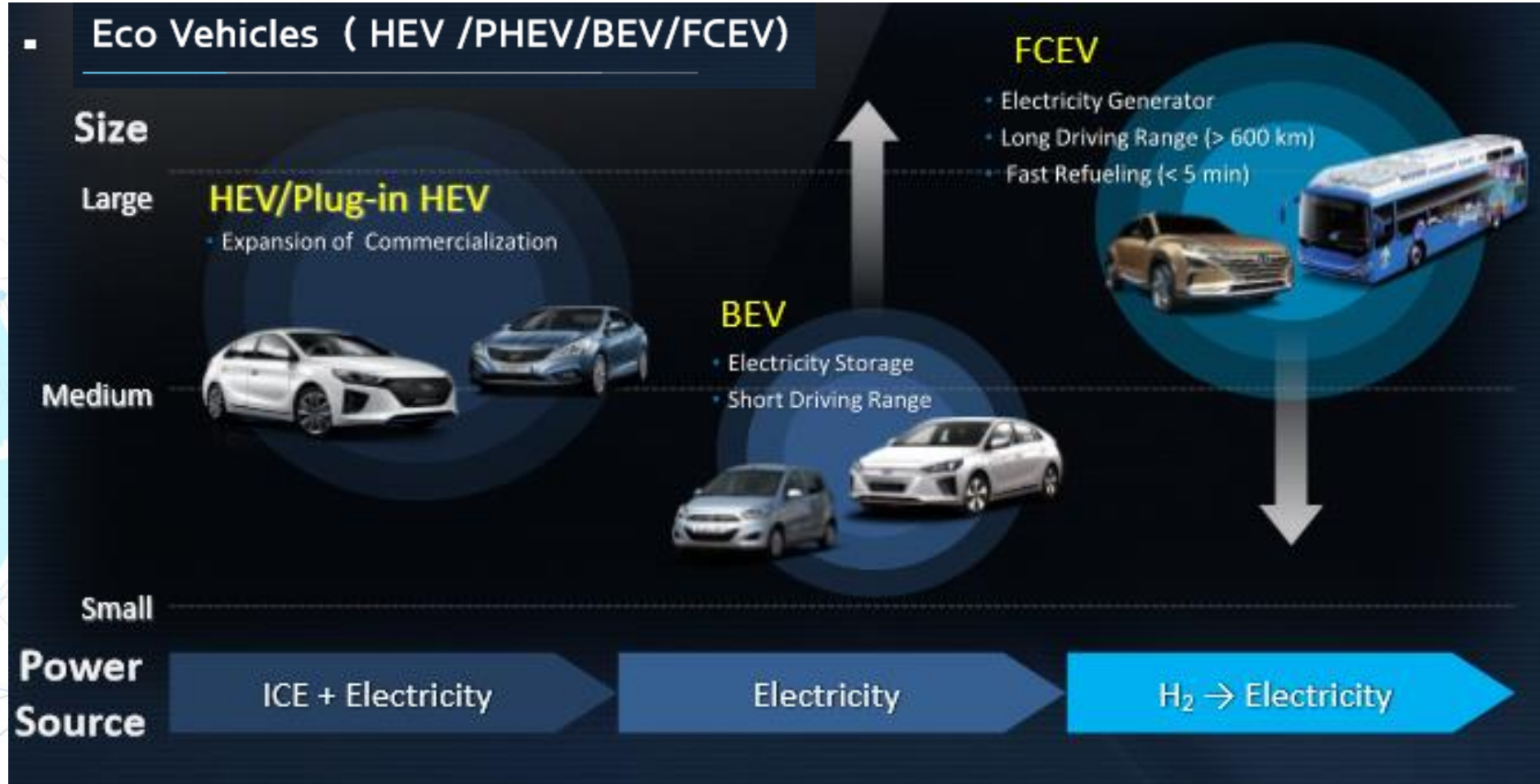
Future Powertrain – Fuel Cell



- Hydrogen has the potential to become the power source of the future, with right infrastructure in place
- Fuel cell Vehicles are emission free compared to Hydrogen ICE Vehicles
- Fuel cell electric vehicles can travel farther and carry more weight than BEV, making them more suitable for longer hauls and heavier loads.
- Hydrogen tanks are also more compact and lighter than an array of fully charged batteries.
- Adding more hydrogen tanks typically costs less than adding more batteries.
- Fuel cell electric vehicles can be refueled within minutes.

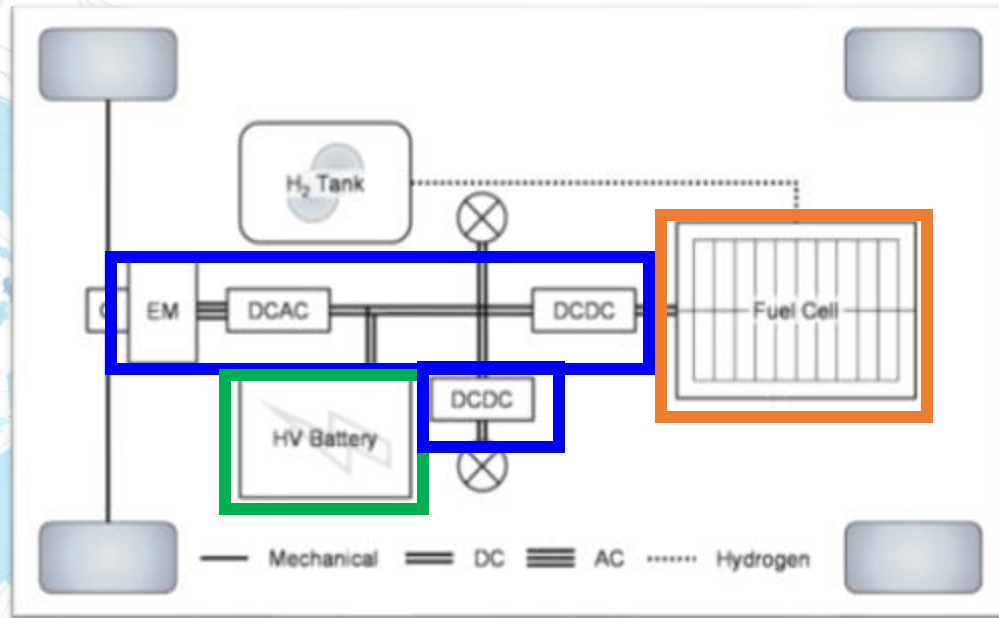


Vehicle classification



Fuel Cell Electric Vehicle

Schematic of a Fuel Cell Vehicle



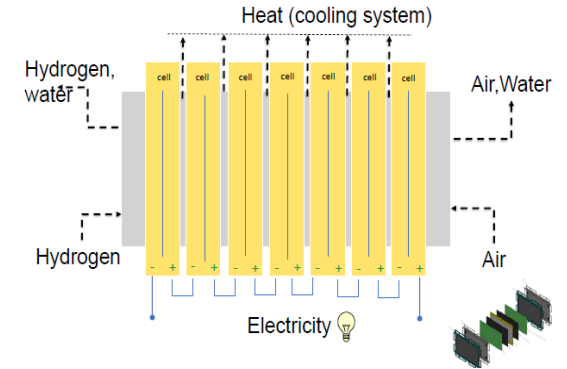
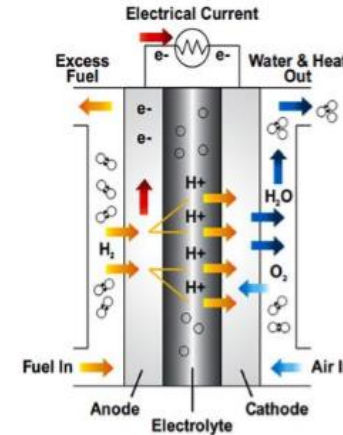
The main systems of a Fuel Cell vehicle are:

- **Fuel Cell stack**
- **Electric machines/motors**
- **Power electronics**
- **Electric energy storage system (batteries)**
- Hydrogen storage system
- Air management system: Compressor or blower
- Water management system: Humidifiers
- Heat/Thermal management system (Cooling system)

Main systems of a Fuel Cell vehicle



- **Fuel cells** are electrochemical devices that convert the chemical energy of a fuel and oxidizer into electricity through a pair of redox reactions.
- Hydrogen is oxidized at the anode with the aid of a catalyst to yield ions that pass through the electrolyte and react with oxygen at the cathode to yield water and heat.
- Fuel cell drives the Motor
- **Power electronics** is a type of solid-state electronics for controlling and converting power.
- Power Electronics system processes and controls the electric power between the FC stack, battery and Electric Motor.
- DC-DC Converter, Fuel Cell BoP.
- Electric machines/motors (EMs), Motor Controller
- **Battery system** allows for storage of electric energy generated from Fuel cells and regenerative braking
- Acts as an energy reservoir and provides supplemental power to the electric traction motor as and when required.
- Usually used battery systems are lithium-ion, nickel-metal hydride and lead-acid batteries.



Source: Indiamart.com



Source: EMPCasting.com



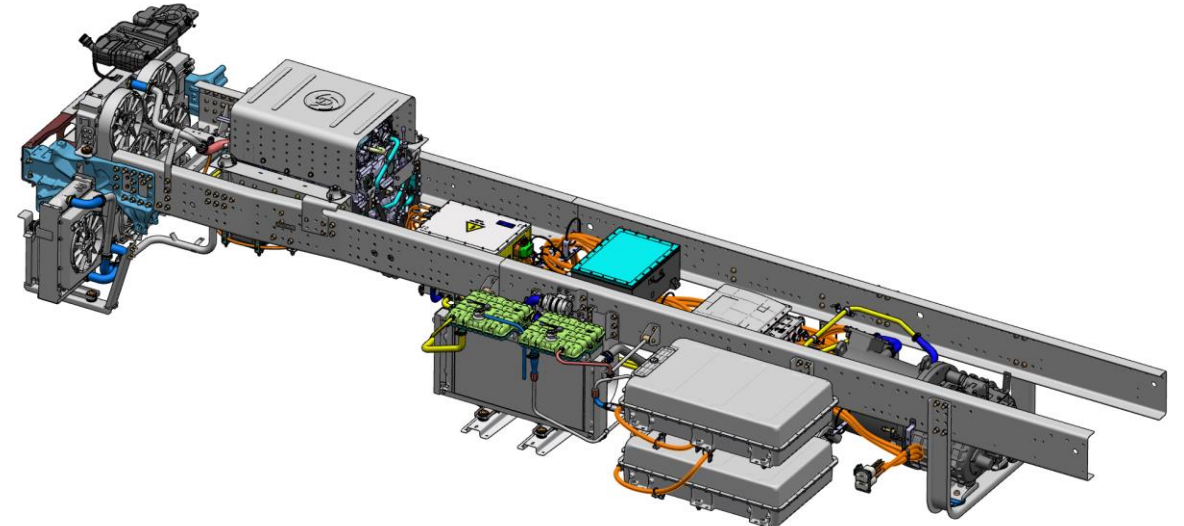
Source: afdc.energy.gov

Ashok Leyland FCET



Vehicle details

Vehicle	6x2 Truck
Model	Fuel Cell (660V)
Application	Haulage
Fuel / Fuel Storage	H2 / H2 Tank
Top speed	70 kmph
Max gradeability	19%
Range	~500 km
Gross vehicle weight (kg)	28000
Cabin type	NGC
AC / Non-AC	Non-AC
Load body capacity(ft)	29.5



Fuel Cell Vehicle Thermal management



- Challenge : Lower operating coolant temperature
- Total Coolant usage in a Fuel Cell vehicle is almost 4 times that of a IC Engine vehicle
- Fuel cell / Battery / PE Components and Motor dissipate heat during its normal functioning
- The working temperatures of the various components are to be within the prescribed limits
- Thermal management systems (Cooling system) of a fuel cell vehicle are broadly classified as below:
 1. Thermal management in Fuel Cell : High temperature Cooling system
 2. Thermal management in Power Electronics components : Low Temperature Cooling system
 3. Thermal management in Battery

Thermal management in Fuel Cell



- Fuel cell has higher heat load demand and Low Coolant temperature requirement
- In Fuel Cell Cooling system electrical conductivity of coolant is significant
- Electrically conductive coolant could cause leakage currents, which reduces FC stack efficiency, lead to coolant electrolysis and possibly cause degradation of bipolar plates.

BOL Fuel Cell Power : 80kW

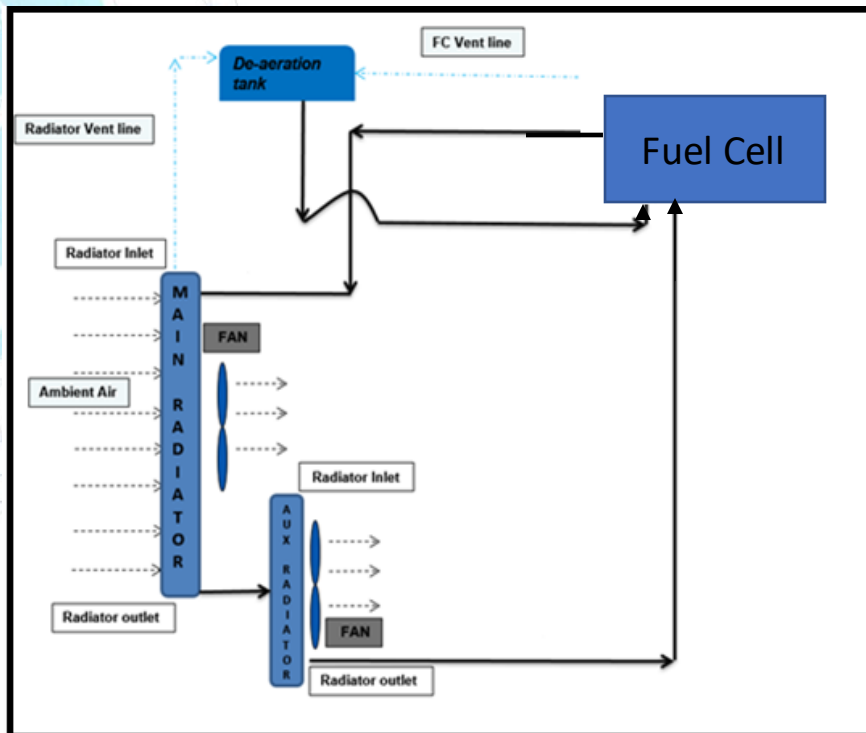
	BOL	EOL
Fuel Cell Heat rejection in kW	105.1	128.4
Coolant Flow rate in LPM	93.6	114.3

HT Cooling System

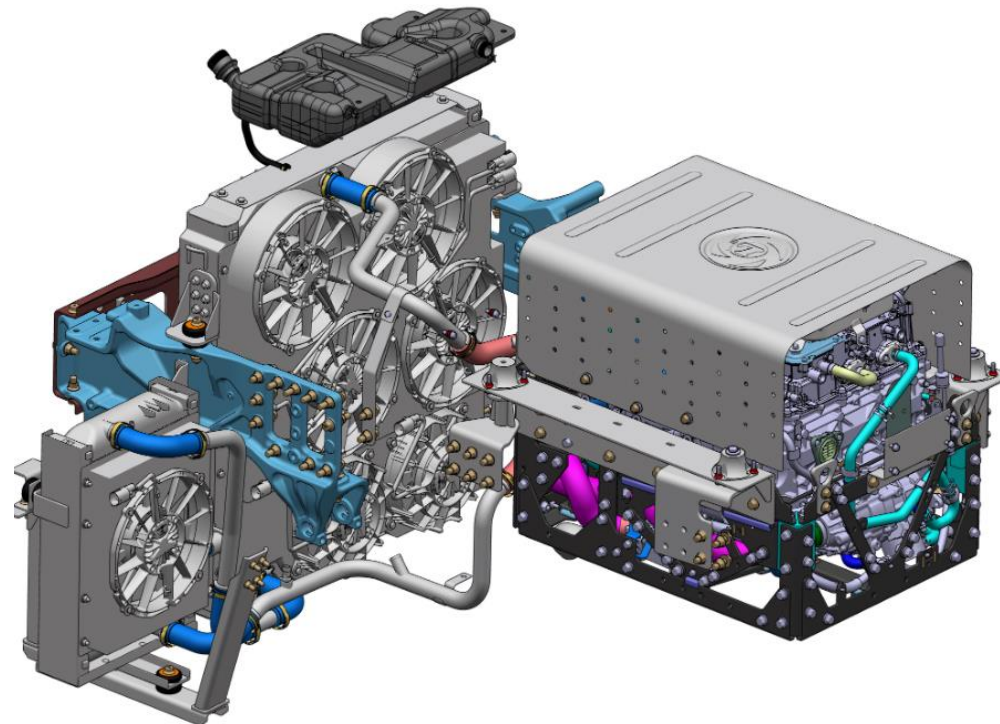
- Main radiator and an auxiliary radiator is used
- Electric fans are used
- Pump is integrated to the Fuel Cell

Radiator core size (w x h x t), mm	Main radiator : 834 X 800 X 74 / Auxiliary radiator : 359 x 430 x 74
Electric fan diameter / nos, Motor wattage, rpm	Main : 305 SPAL / 4, 720 W, 4750rpm 255 SPAL / 2, 360 W, 4300rpm Aux : 305 SPAL / 1, 720 W, 4750rpm

HT Cooling Circuit



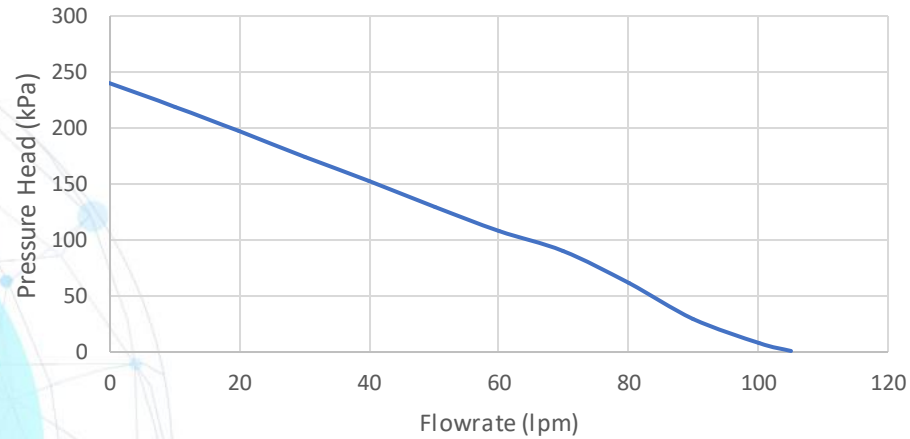
Layout



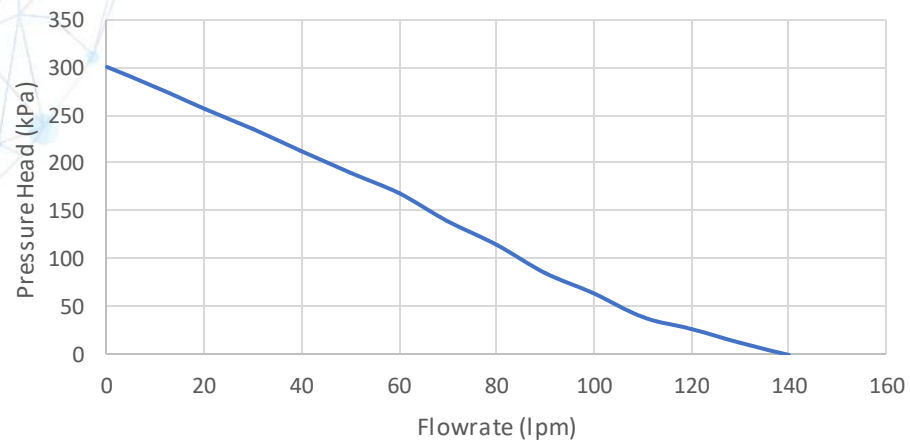
KULI inputs of FC components



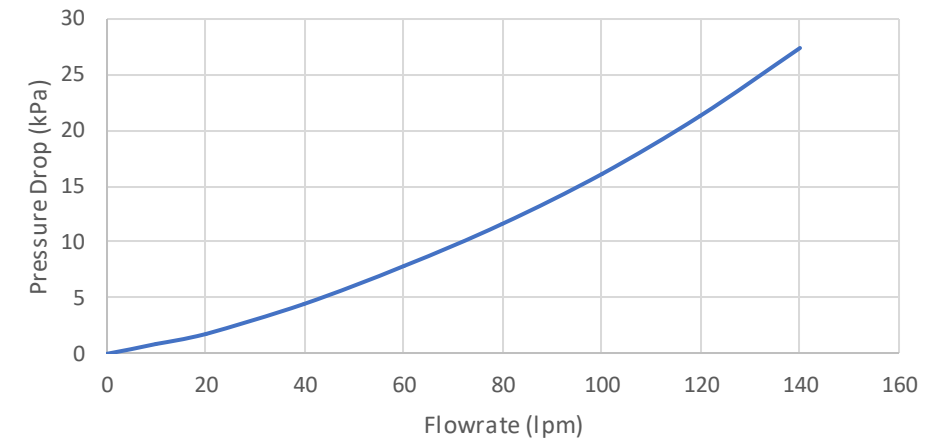
Pump characteristics - BOL



Pump characteristics - EOL

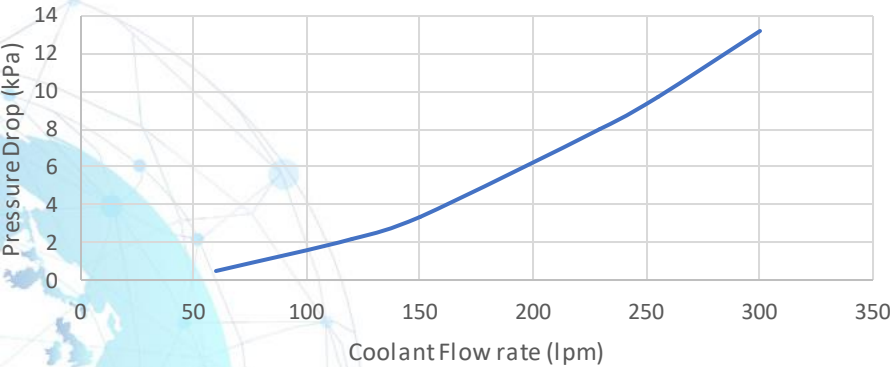


Fuel cell restriction

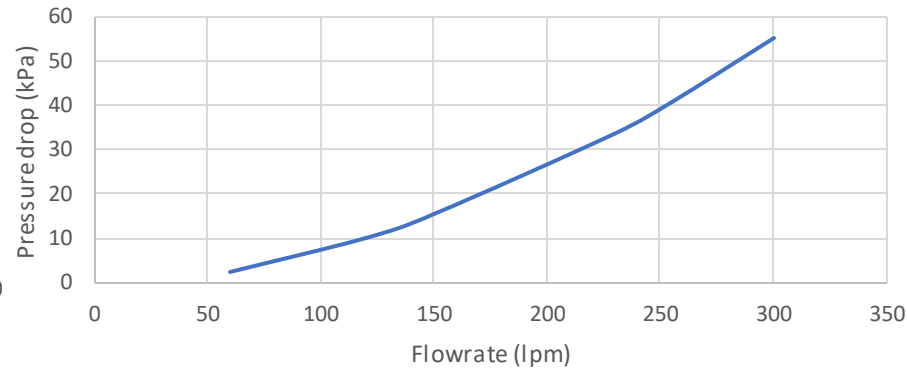


KULI inputs of FC components

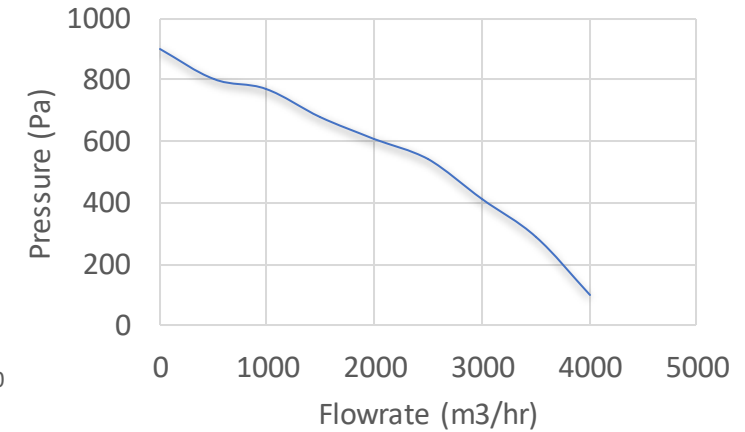
HT Main Radiator – Inner Flow
Pressure drop (kPa)



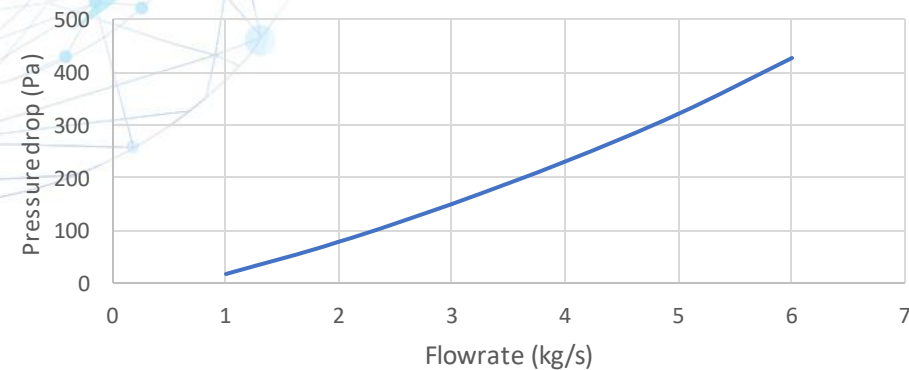
HT Aux Radiator - Inner Flow
Pressure drop (kPa)



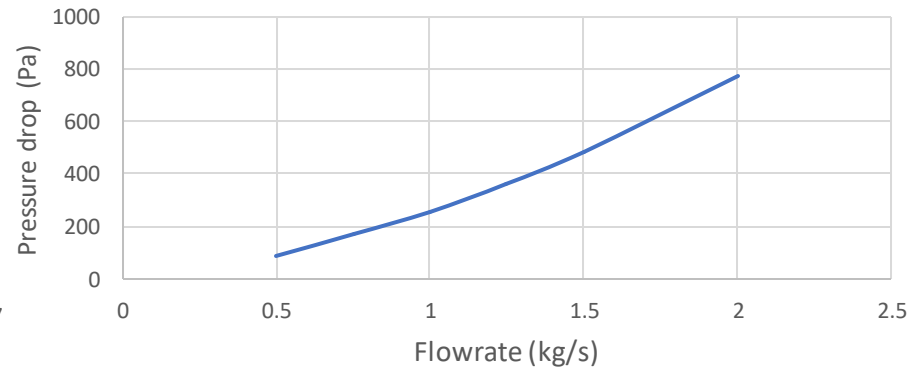
Electric Fan – 305 dia



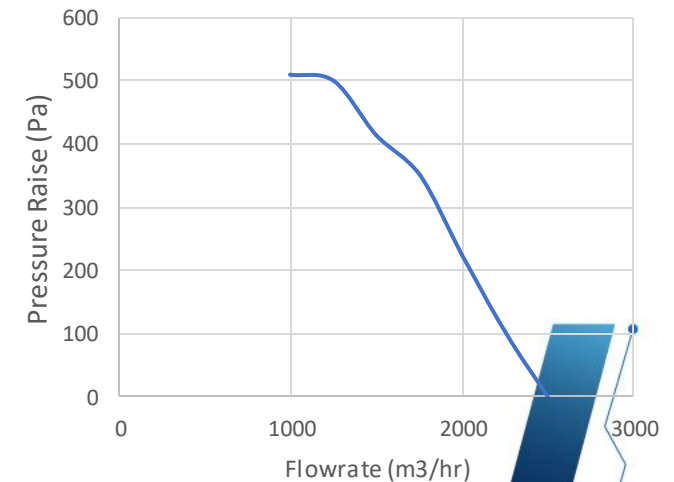
HT Main Radiator - Outer Flow
Pressure drop (Pa)



HT Aux Radiator - Outer Flow
Pressure drop (Pa)

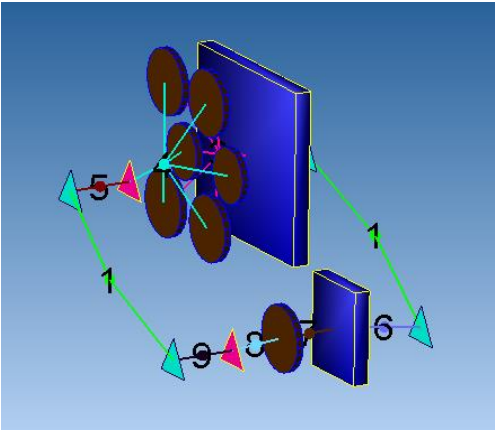


Electric Fan – 255 dia

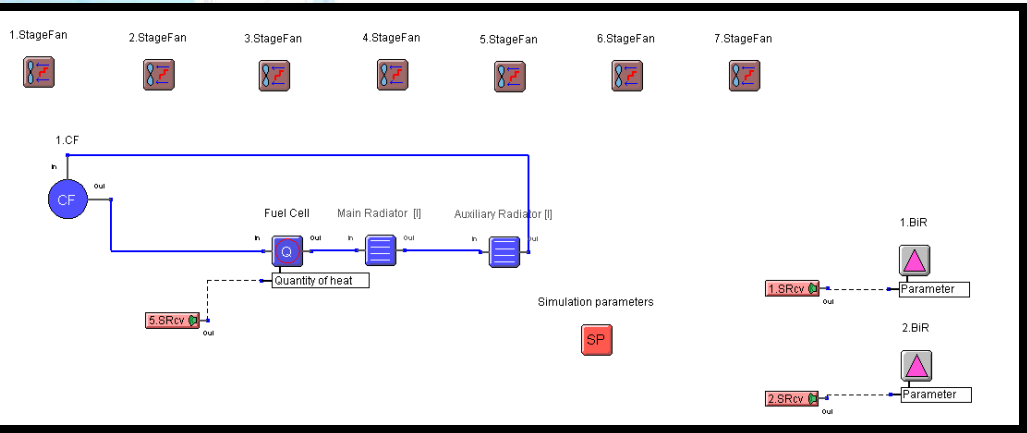


HT Cooling System – KULI prediction

KULI 3D view



KULI Circuit



	Parameters	Units	BOL	EOL
Input	Heat Load	kW	105.1	128.4
	Coolant Flow rate	lpm	93.6	114.3
	Ambient	° C	45	45
	Warmup	° C	5	5
	Fan speed	rpm	4750rpm x 5 Nos (305 fan), 4300rpm x 2 Nos. (255 fan)	
	BIR Rad 1		20	
	BIR Rad 2			
Output	Radiator 1 Inlet temp	° C	78.6	84.1
	Radiator 1 Outlet temp	° C	63.1	68.9
	Radiator 2 Outlet temp	° C	59.5	66.1
	Delta T across radiators	° C	19.1	18

Power Electronics components



- Power electronics is a type of solid-state electronics for controlling and converting power.
- Power Electronics system processes and controls the electric power between the FC stack, battery and Electric Motor.
- Electric machines/motors (EMs) : Using power from the traction battery pack/fuel cell, motor drives the vehicle's wheels.
- Motor Controller: This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces. It regulates the power to the EM. This inverter converts DC power from the FC stack or battery to Alternating Current power for the EMs.
- DC-DC Booster: This unit converts the battery output voltage to required high voltage.
- DC-DC Converter: This unit converts the high voltage DC output power from the DC DC booster to the lower-voltage DC power needed to run vehicle accessories and power the auxiliary loads of the vehicle, (Radiator Fan, Electrical components like LED lamps etc) and to recharge the auxiliary battery.
- Fuel Cell BoP: Auxiliary components inside Fuel cell required to ensure proper functioning of a fuel cell.
- Auxiliary inverter: This unit converts DC power to AC power for use in components like Steering Pump, AC Compressor

Thermal management in Power Electronics components



- The Power Electronics system processes and controls the electric power between the FC stack, battery and Electric Motor.
- The key components of PE system are Motor, Controller, DC-DC converter and Fuel Cell BoP.
- During their functioning heat is generated. This heat is to be dissipated properly to ensure that the working temperatures of the various components are kept within the prescribed limits.
- Power Electronics cooling system (Traction Cooling System) in FC vehicles keeps the PE components temperature at its optimal range. Liquid cooling system is used.
- PE components are connected by Coolant path in Series or Parallel depending on the flow and temperature requirements.

Components of PE system

E-Motor Peak power/torque : 360kW/3000Nm

Continuous power/Torque : 260kW/1600 Nm

The DC-DC converter converts the high voltage DC power 400-850V/11A(Max) to DC power of 28V/142A

Thermal management in Power Electronics components



Heat rejection, Inlet temperature and Coolant flow rate targets of Low temperature Cooling system are as listed below.

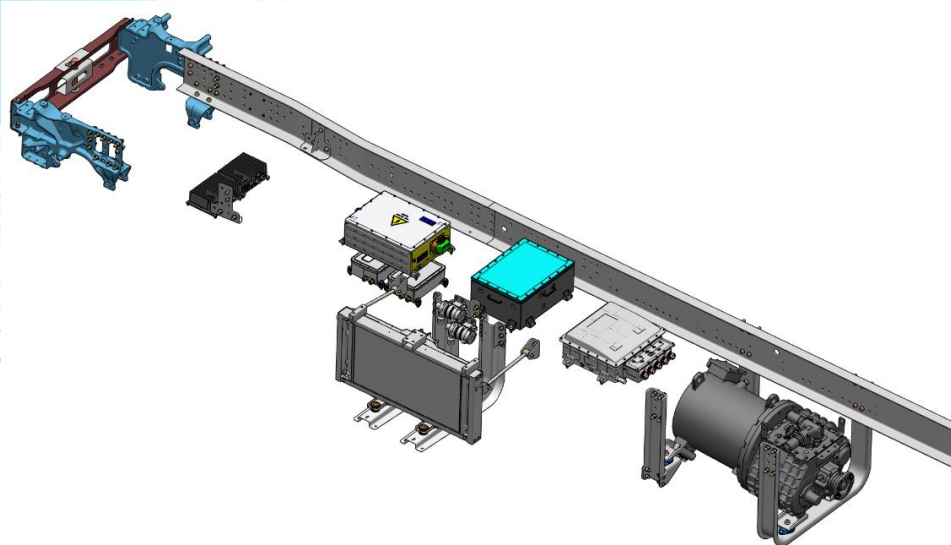
Component	Heat Rejection	Inlet temperature Target	Coolant Flowrate Target
Motor	14.66 kW	$\leq 65^{\circ} \text{ C}$	$\geq 40 \text{ LPM}$
Motor Controller	9 kW	$\leq 65^{\circ} \text{ C}$	$\geq 25 \text{ LPM}$
DC-DC Converter - Two qty	0.2 kW each	$\leq 70^{\circ} \text{ C}$	7 TO 10 LPM
Fuel Cell - BoP	7 kW	$\leq 65^{\circ} \text{ C}$	$\geq 12 \text{ LPM}$
TOTAL HEAT REJECTION	31 kW		

LT Cooling System

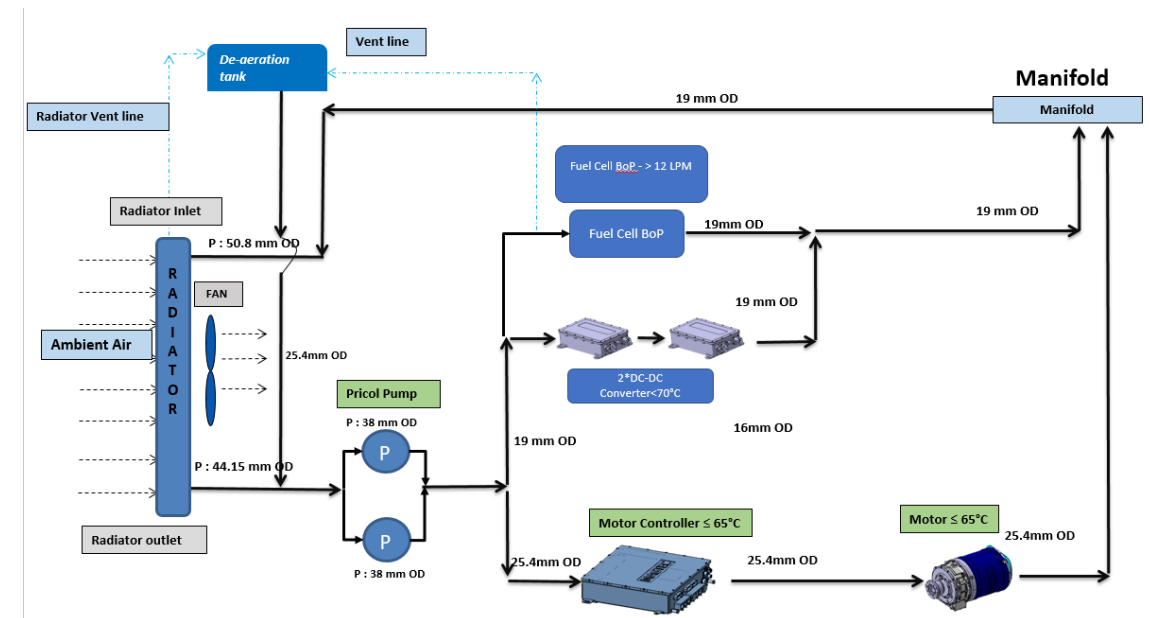
- Pipes and hoses are used to connect the Coolant flow path
- Radiator with Electric fans are used

Radiator core size (W x H x T), mm	800 X 447 X 34
Electric fan diameter / nos, Motor wattage, rpm	305 SPAL / 2, 720 W, 4750rpm max. 255 SPAL / 1, 360 W, 4300rpm max
Pump	24V DC, rated current < 15A, 4800rpm

Layout



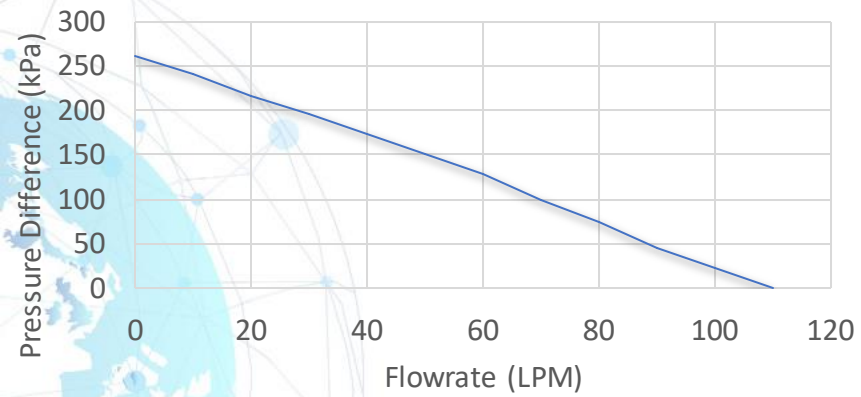
LT Cooling Circuit



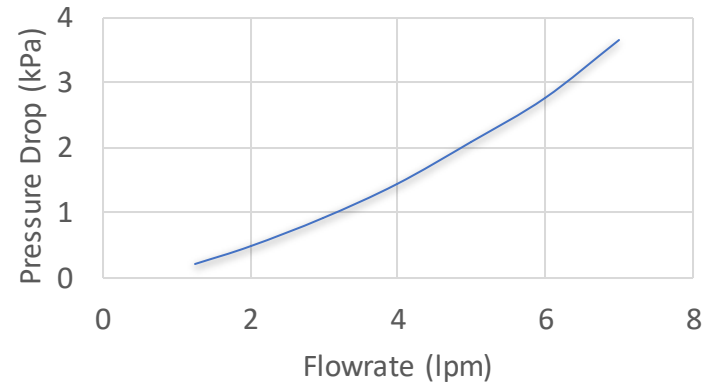
KULI inputs of PE components



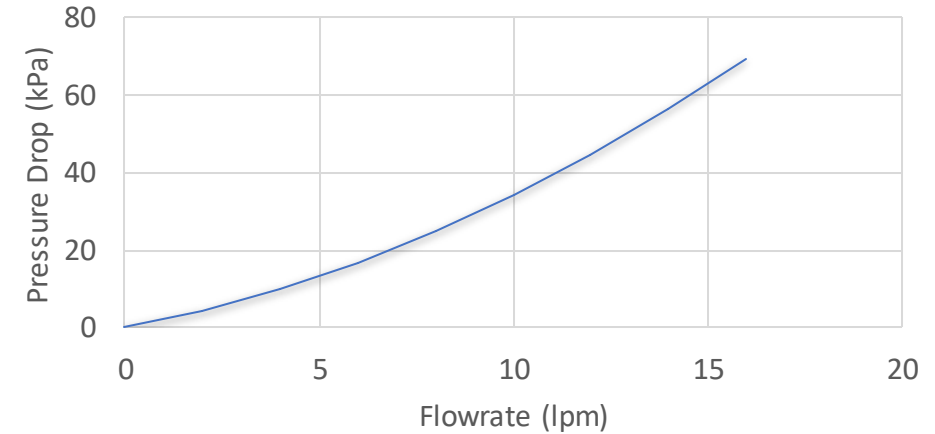
Coolant Pump



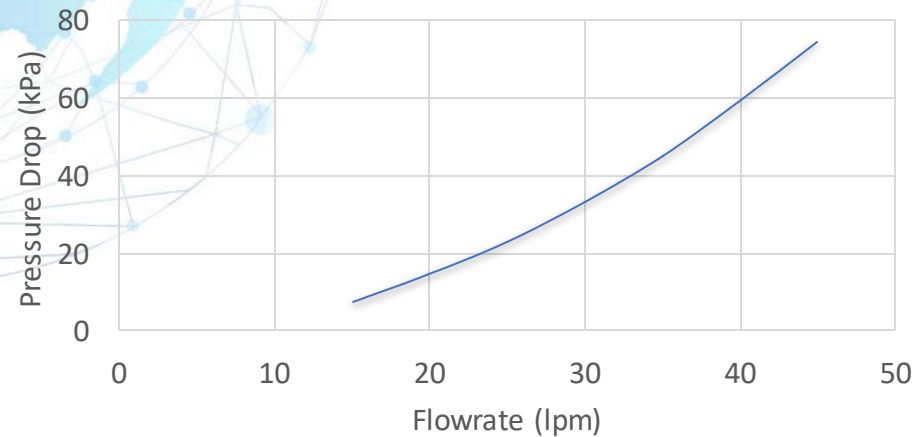
DC-DC Converter



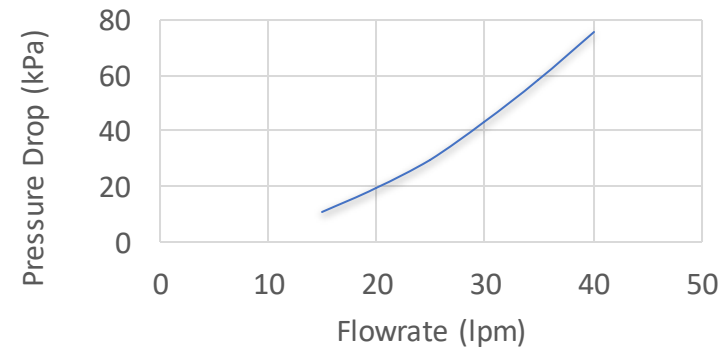
Fuel Cell BOP



Traction Motor

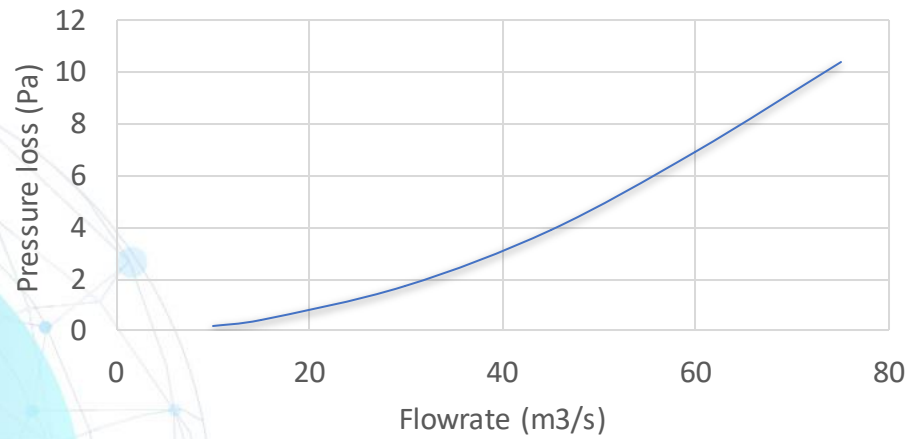


Motor Controller

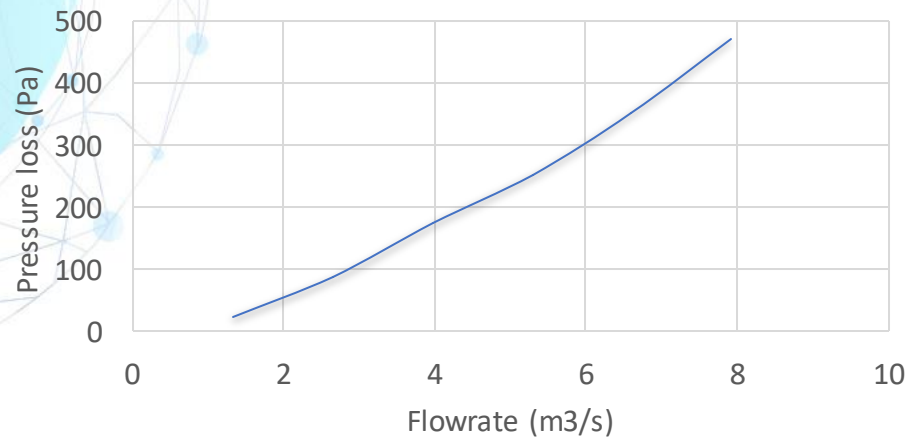


KULI inputs of PE components

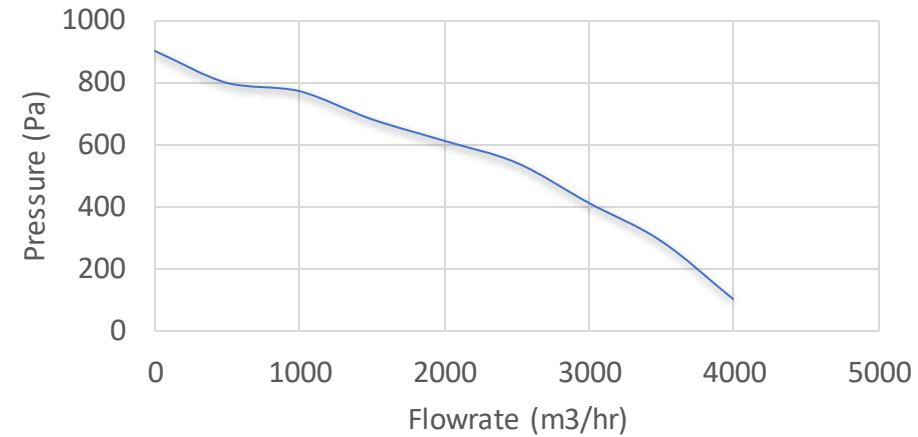
Radiator Inner flow



Radiator Outer Flow



Electric Fan – 305 dia



Pipes and hoses

Tube ID: 4.TUB

Comment: Hose Pump Out 1

Calc. method for pressure drop
☒ Standard
☐ Miller

Inner diameter [mm]: 37
 Pipe roughness [mm]: 0.08
 Tube length [mm]: 160

Bend ID: 2.BND

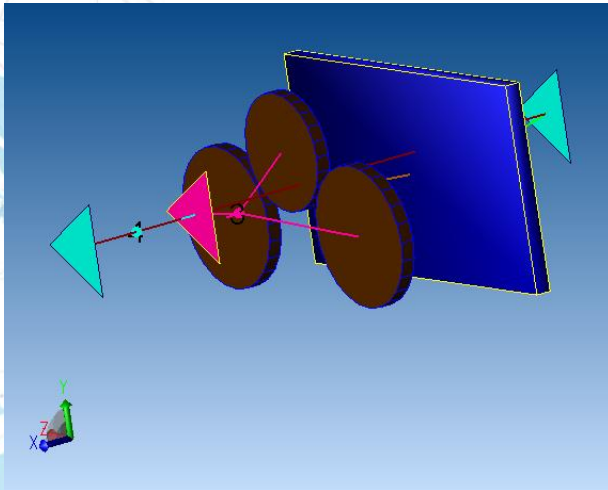
Comment: L Bend Hose 18dia

Calc. method for pressure drop
☒ Standard
☐ Miller

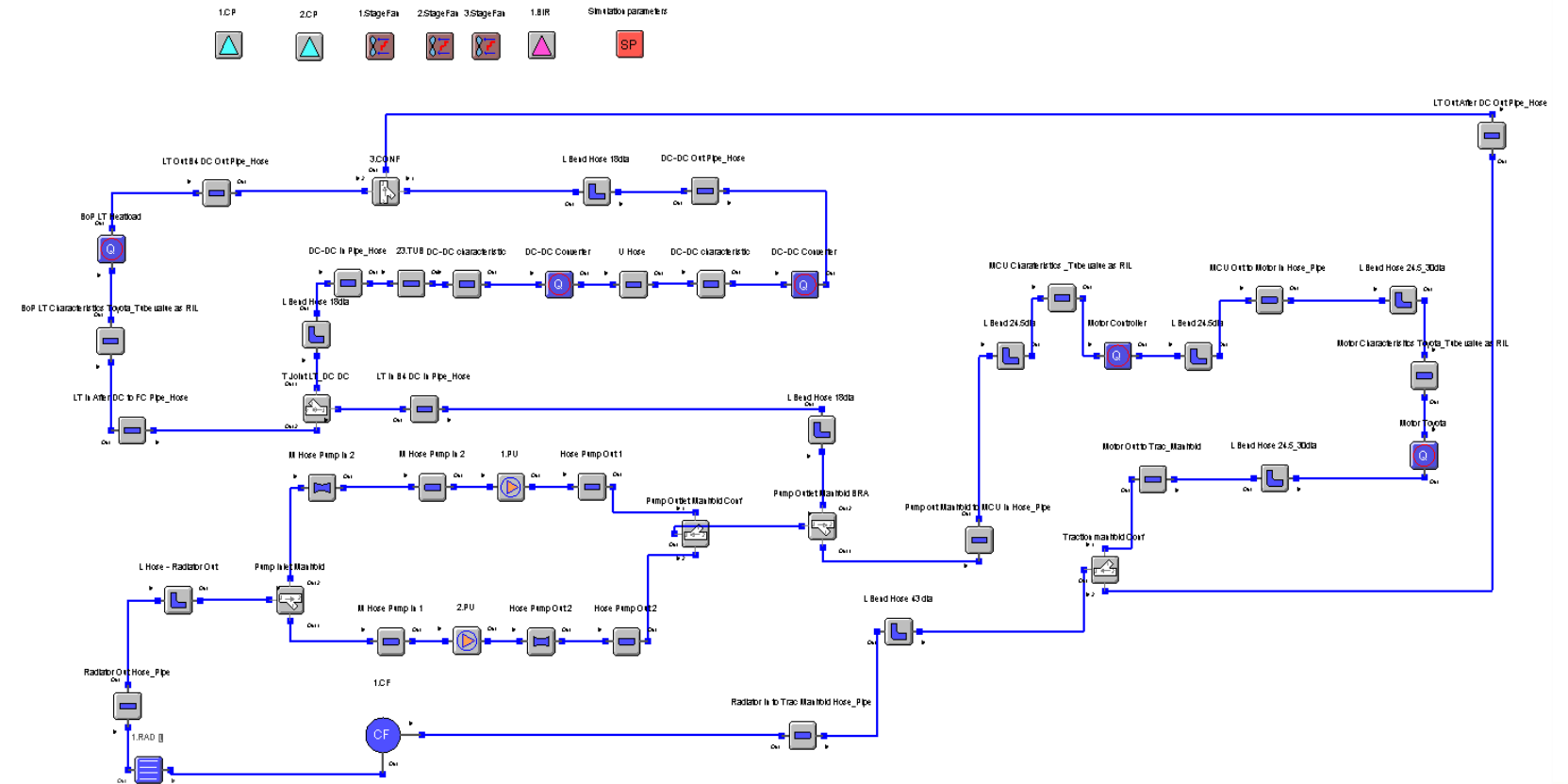
Inner diameter [mm]: 18
 Pipe roughness [mm]: 0.08
 Angle of deflection [°]: 90
 Curvature radius [mm]: 40

LT Cooling System – KULI prediction

KULI 3D view



KULI Circuit



LT Cooling System – KULI prediction

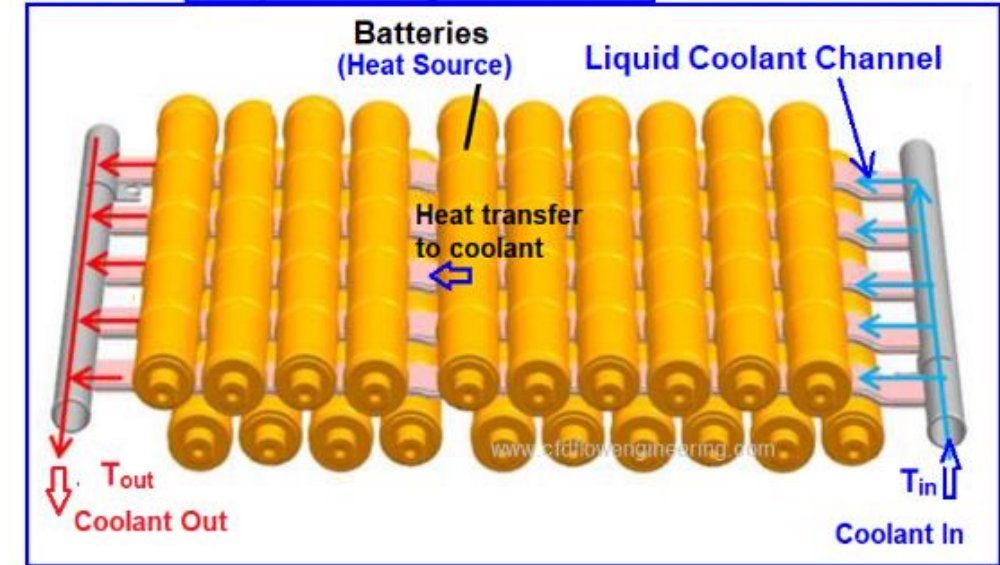


Component	Flow rate Requirement (lpm)	Flow rate Predictions (lpm)	Inlet Temperature Target(° C)	Inlet Temperature Predicted(° C)
Radiator	NA	74.7	NA	67.7
Pump 1	NA	37.2	NA	60.9
Pump 2	NA	37.2	NA	60.9
Traction Motor Controller	≥ 25 LPM	42	≤ 65	60.9
Traction Motor	≥ 40 LPM	42	≤ 65	64.3
DC-DC Converter 1	7 TO 10 LPM	10	≤ 70	60.9
DC-DC Converter 2	7 TO 10 LPM	10	≤ 70	61.2
Fuel cell BoP	≥ 12 LPM	22	≤ 65	60.9

Thermal management in Battery

Charging and Discharging the battery generates heat; the more rapidly a battery discharges, the more heat it generates.

Potential thermal stability issues, such as capacity degradation, thermal runaway, and fire explosion, could occur if the battery overheats or if there is non-uniform temperature distribution in the battery pack.



Battery thermal system has to meet the need of

Battery Coolant inlet temperature $< 18^{\circ}\text{C}$

Coolant flow rate of 6-20 lpm.

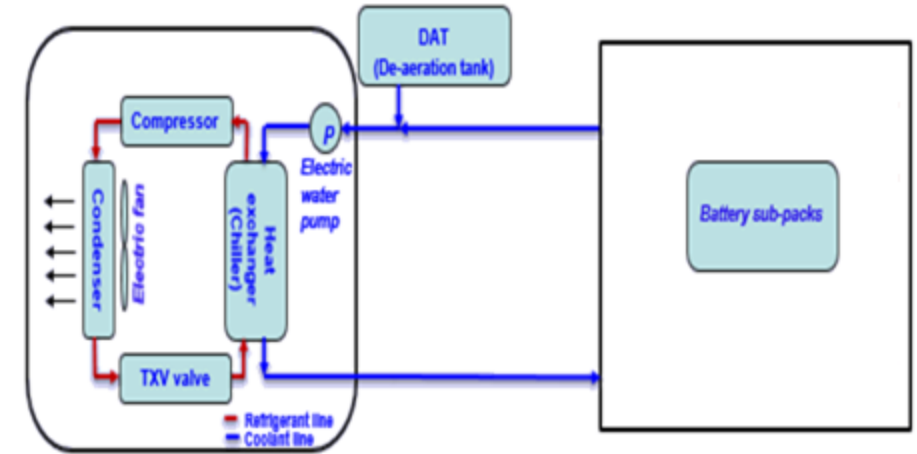
Working temperature range of Battery packs (Cell temp) : 20°C to 35°C .

Heat rejection from each battery : 3.5kW at 3.5C discharge rate

Battery Cooling system

A two loop cooling system is used in Battery

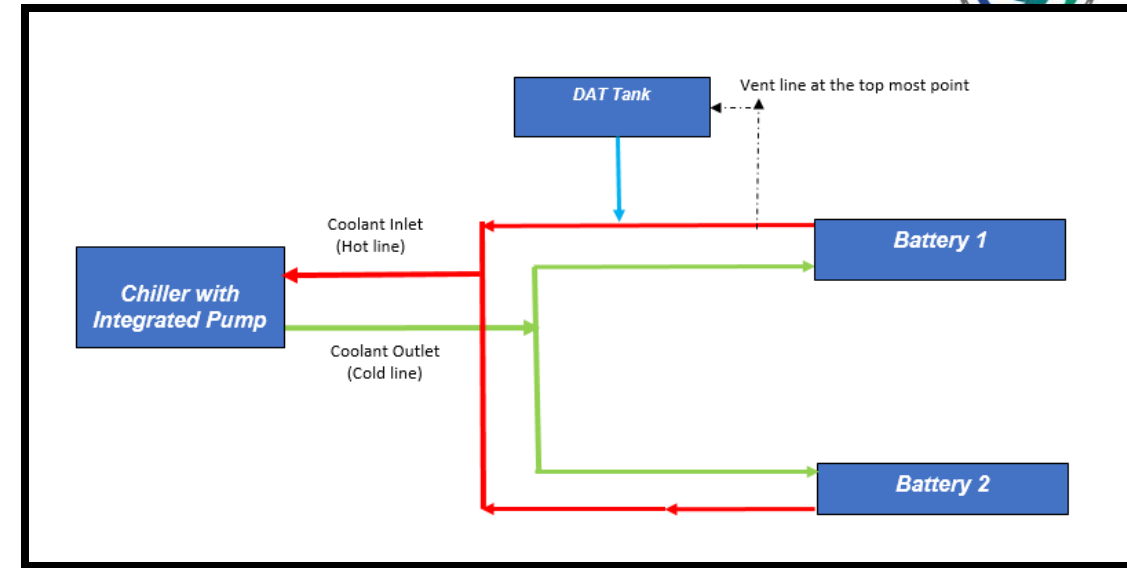
1. The first loop (primary loop) consists of pump, pipes, battery and has coolant as the flow medium. Coolant flow is driven by a pump to the batteries at required inlet temperature. The coolant absorbs heat from the batteries and is circulated through a chiller.
2. The second loop (secondary loop), BTMS works similar to an AC system. It consists of compressor, condenser, expansion valve and Heat exchanger and uses refrigerant as the flow medium.



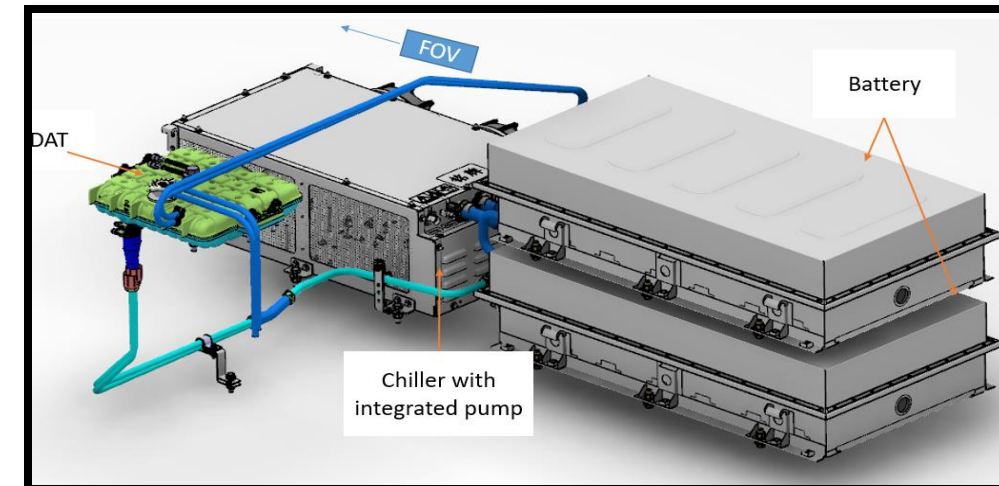
Battery Cooling system



Battery Cooling Circuit



Layout



Total energy stored in Battery : 47.95kWh

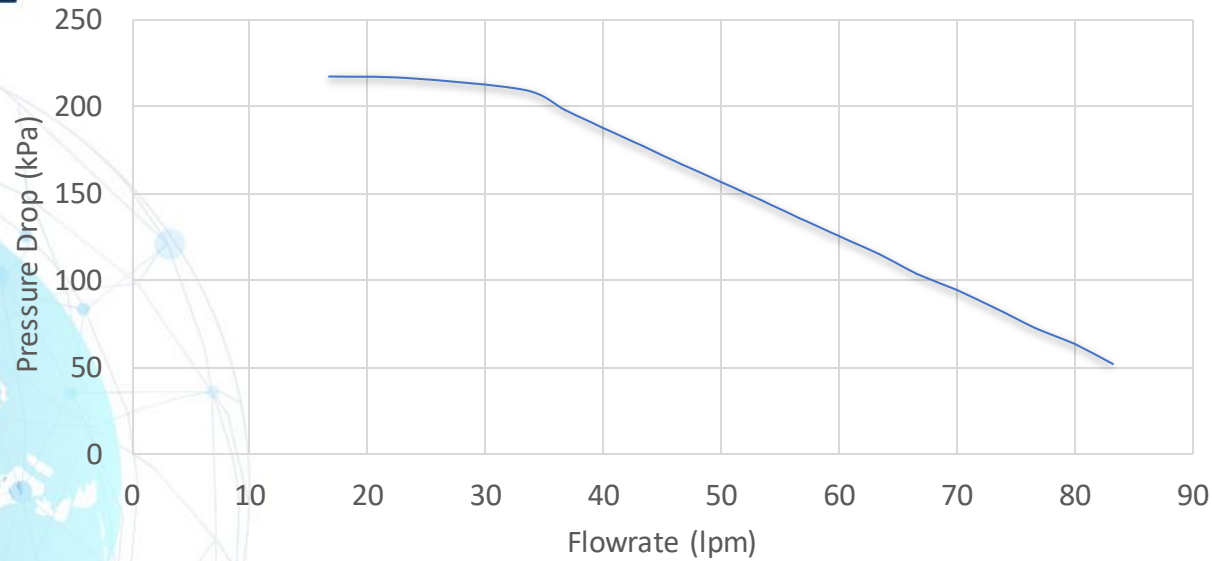
Nominal voltage : 666V and operating range : 486 to 756V

Charge capacity : 72Ah

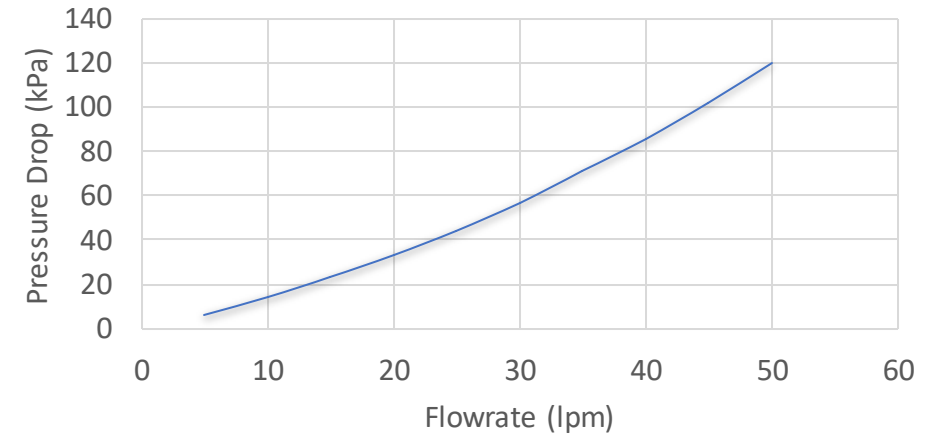
- Pipes and hoses are used to connect the Coolant flow path.
- Two batteries are connected in parallel to obtain the maximum coolant flow and simplicity in connection.
- For cooling, the heat is transferred from coolant to refrigerant in Chiller.
- A 24V DC electric pump is used which runs at 4500rpm to deliver the required coolant flow to batteries.

KULI inputs of Battery Cooling system

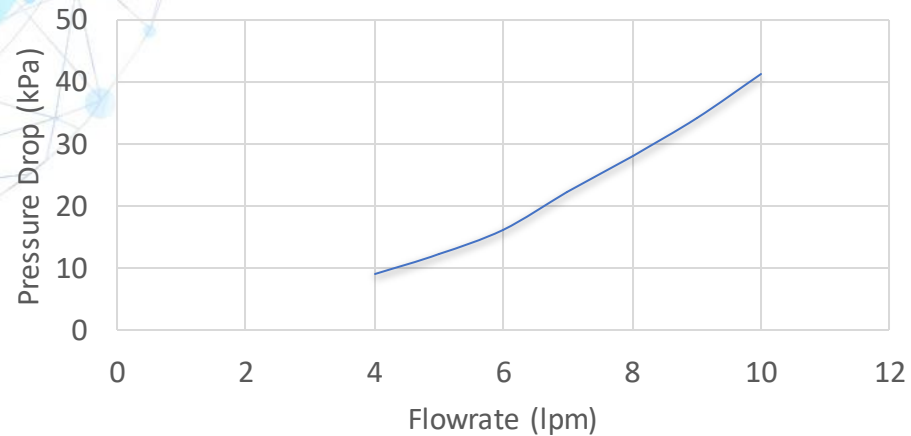
Pump Characteristics



Chiller

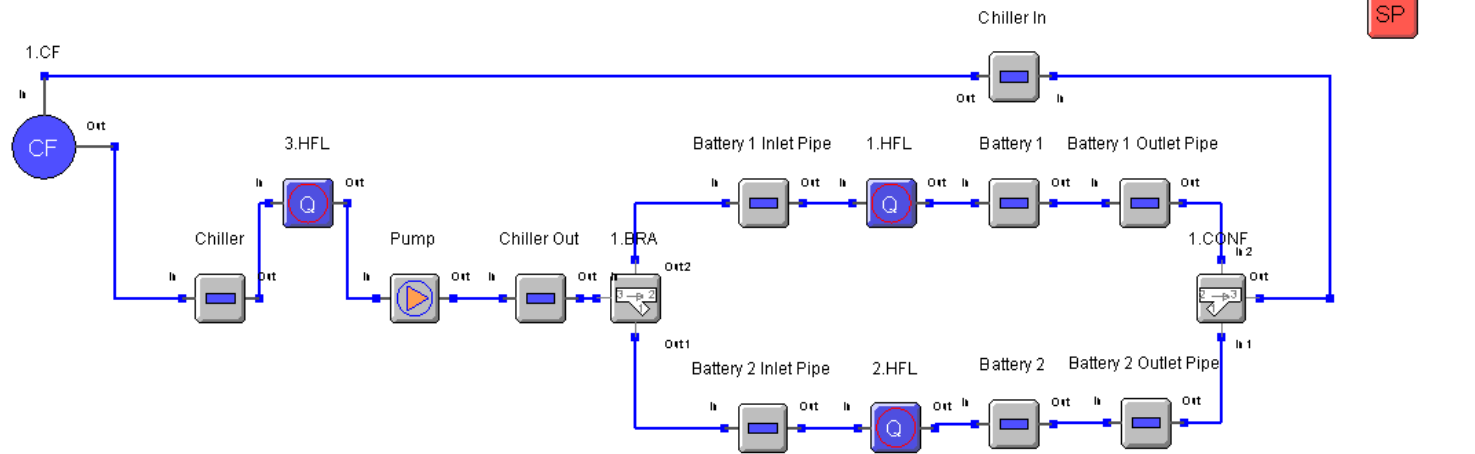


Battery



Battery Cooling System – KULI prediction

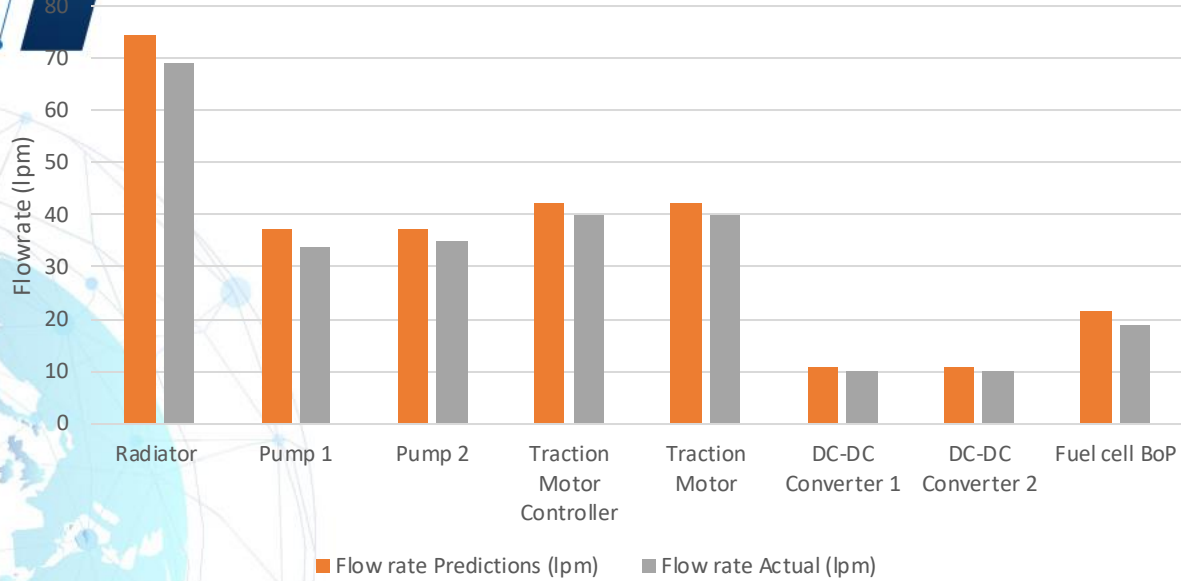
KULI Circuit



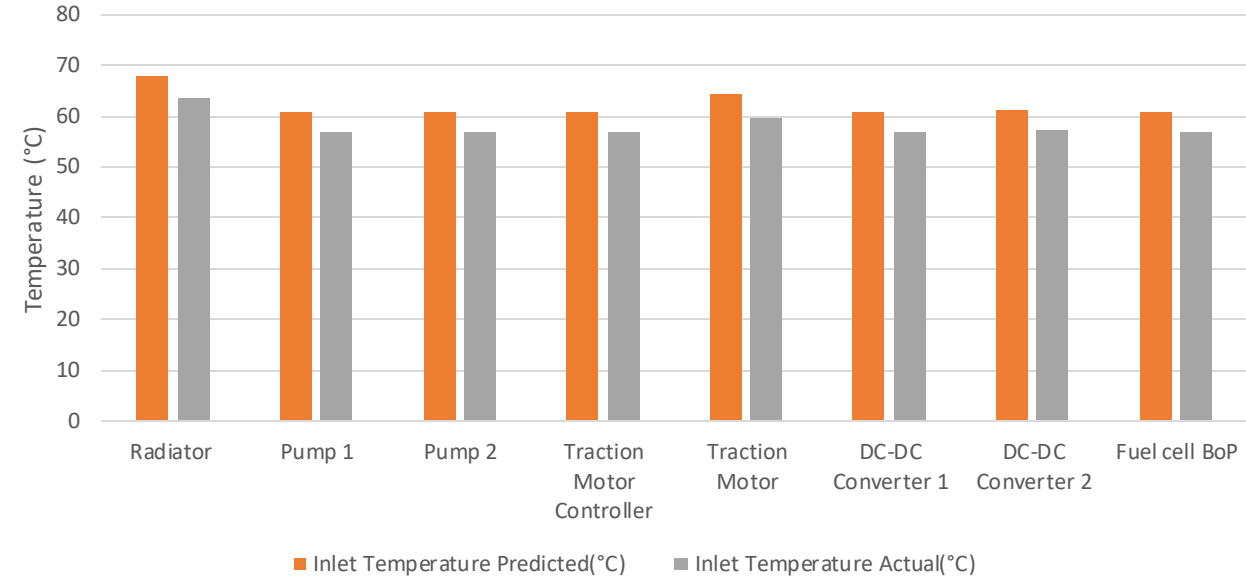
Component	Coolant flow rate target (lpm)	Coolant flow rate prediction (lpm)	Battery Coolant Inlet Temperature Target max (° C)	Battery Coolant Inlet temperature prediction (° C)	Battery Coolant outlet temperature prediction (° C)
Battery 1	6 - 18	17.1	18	16.5	20
Battery 2	6 - 18	17.1	18	16.5	20

KULI prediction VS Test results

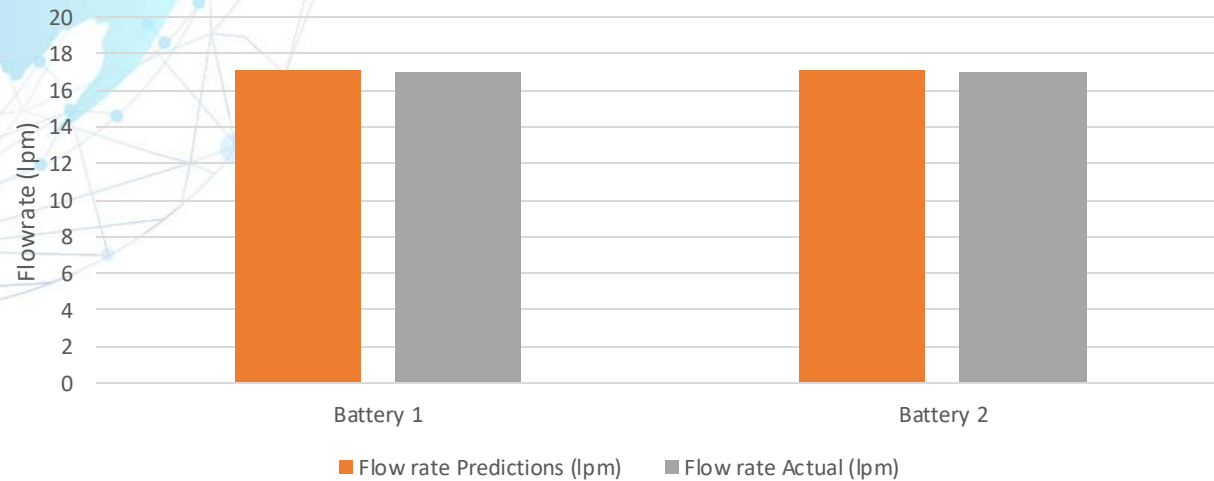
PE Cooling System Flowrate - Prediction vs Actual



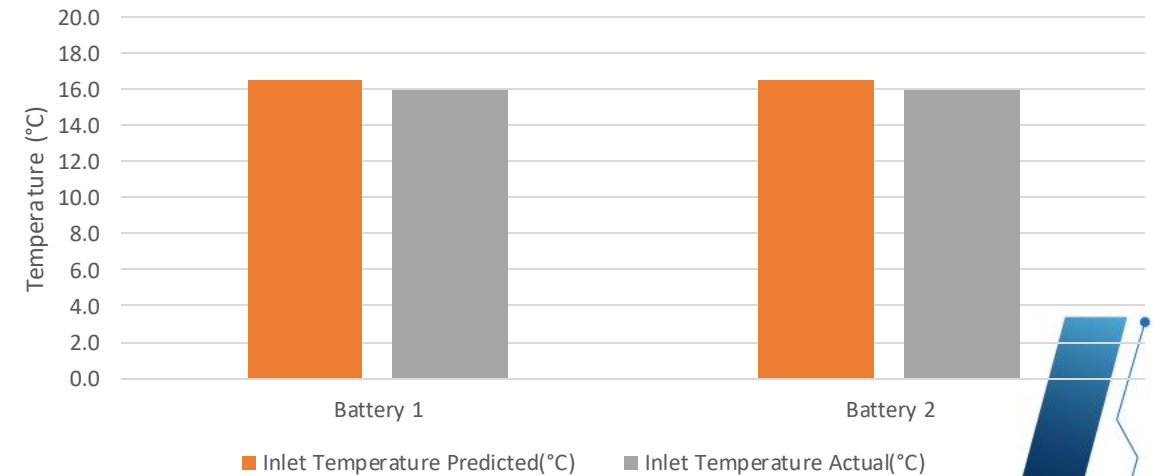
PE Cooling System Inlet Temperature - Prediction vs Actual



Battery Cooling System Flowrate - Prediction vs Actual



Battery Cooling System Inlet Temperature - Prediction vs Actual



Conclusion



- ❑ Thermal management system in a Fuel Cell Truck is explained
- ❑ KULI simulation and predictions are demonstrated in HT, LT and Battery Cooling system
- ❑ Correlation is achieved within 5 to 10%
- ❑ Further this approach will be carried forward for Fuel Cell Bus.



Thank You

