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Development of Fuel Cell System Simulator

S. Hasegawa [a,b], Y. Ikogi [b], S. Kim [c], M. Kageyama [a], and M. Kawase [a]

[a] Department of Chemical Engineering, Kyoto University
[b] Commercial ZEV Product Development Div. Toyota Motor Corporation
[c] Department of Applied Physics and Chemical Engineering, Tokyo University of Agriculture and Technology

s.hasegawa@cheme.kyoto-u.ac.jp

Outline

1. Background
   - Overview of fuel cell (FC) system
   - Challenges in FC system development process

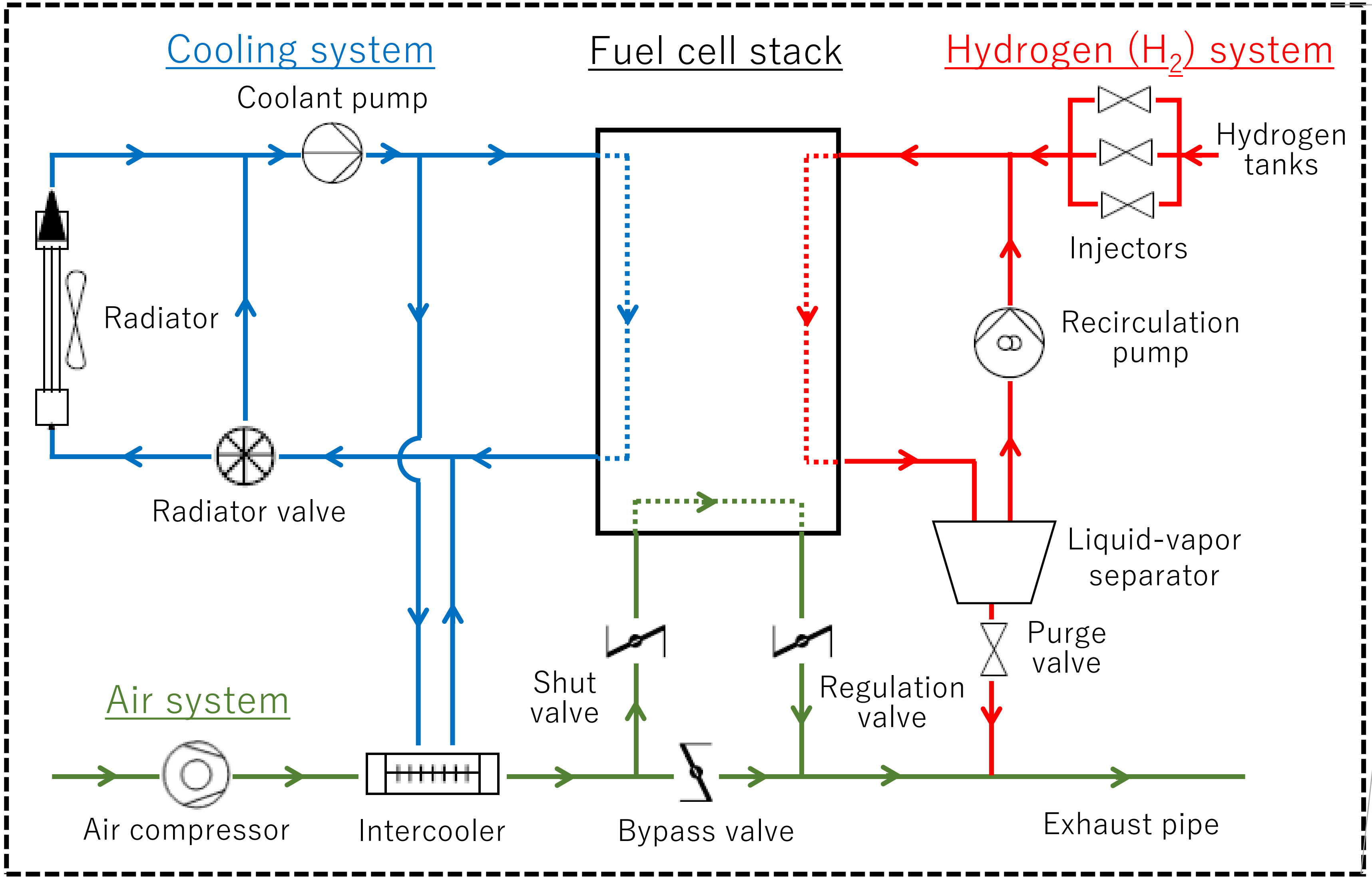
2. Integrated fuel cell system simulator FC·DynaMo

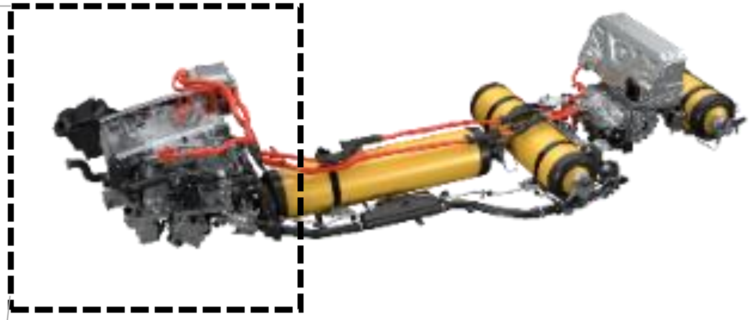
3. Modeling methods of FC system
   - FC system component models
   - Numerical methods
   - Efficient Implementation methods to MATLAB®/ Simulink®
   - Parameter determination

4. Model validation & verification by database collected with state-of-the-art commercial FCEV, 2nd-generation MIRAI

5. Simulation results of overall FC system dynamics

1. Background : Overview of fuel cell (FC) system



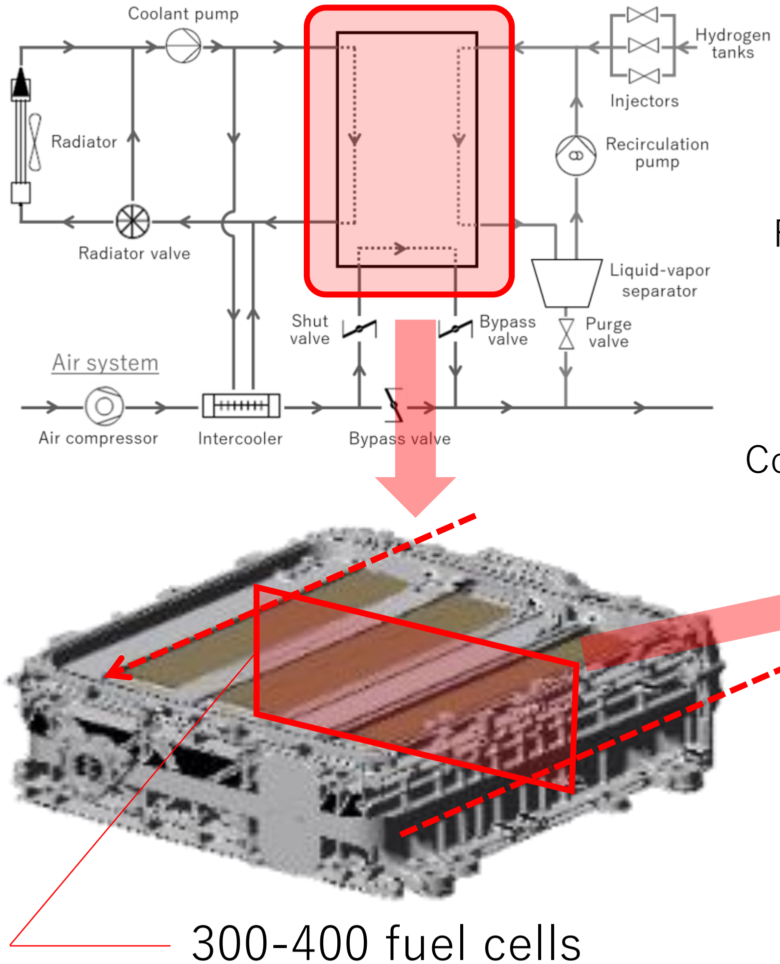


	ICE-system	FC-system
Main engine	Internal combustion engine	FC-stack
sub-systems	Air intake system	Air system
	Fuel injection system	H_2 system
	Cooling system	Cooling system

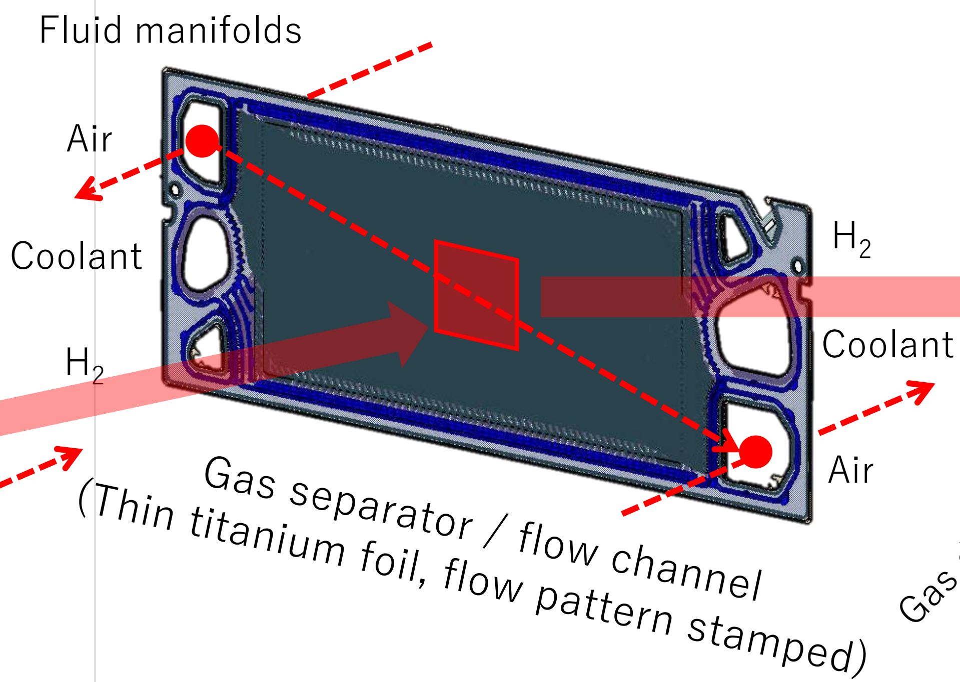
FC-stack as main engine and 3 subsystems of air, H_2, and cooling system
Similar configuration as internal combustion engine system

1. Background : Fuel cell stack

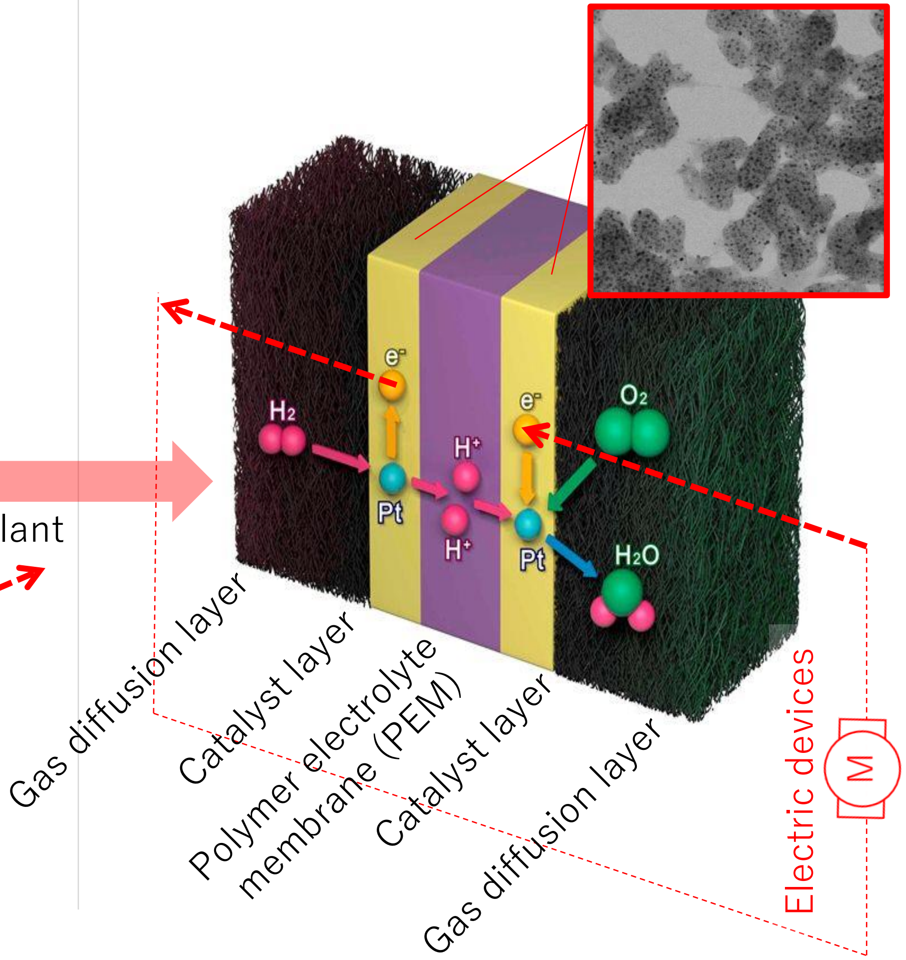
Fuel cell (FC) stack



Fuel cell
(7-layer sandwich structure)

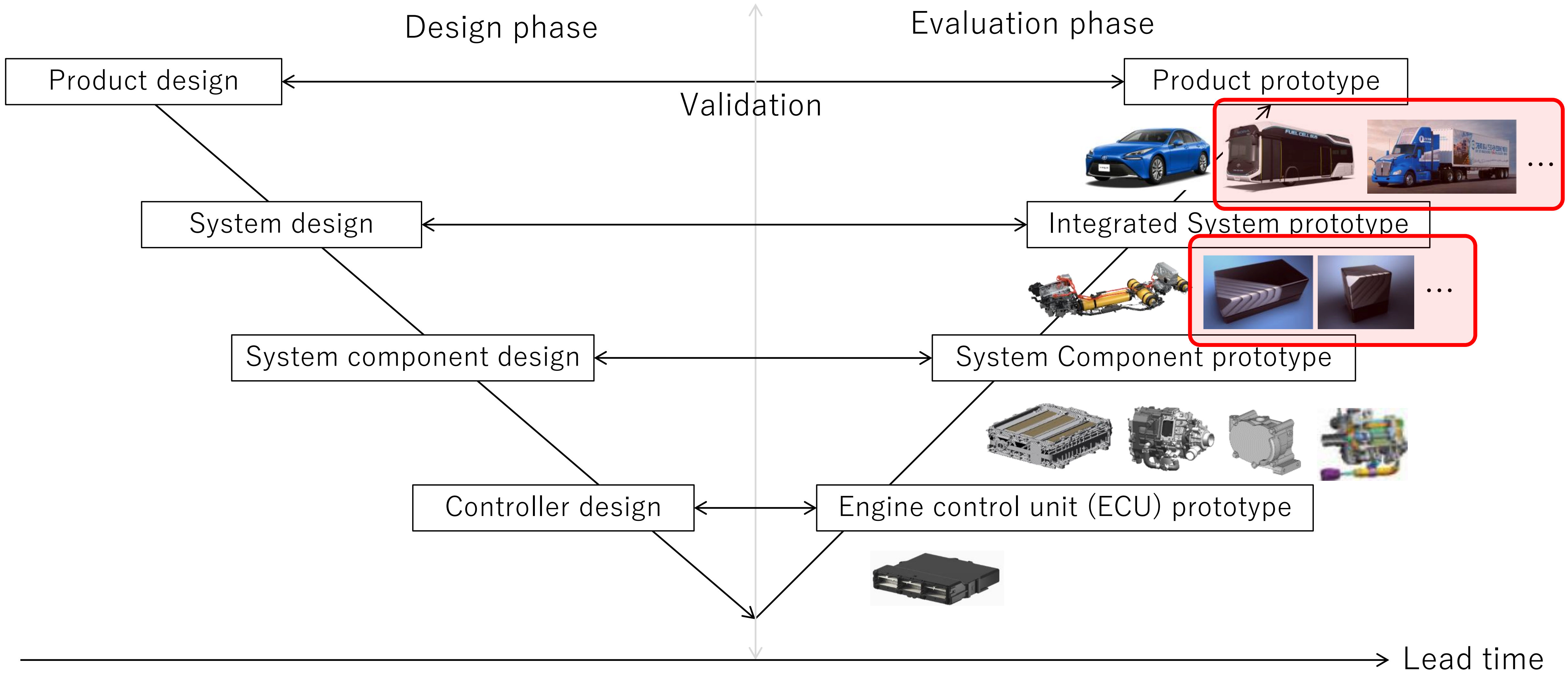


Power generation element
(MEA = Membrane Electrode Assembly)



Reactants (H_2 and O_2) are supplied to the catalyst layers through the flow channels
Generated electric power is delivered to the external electric devices

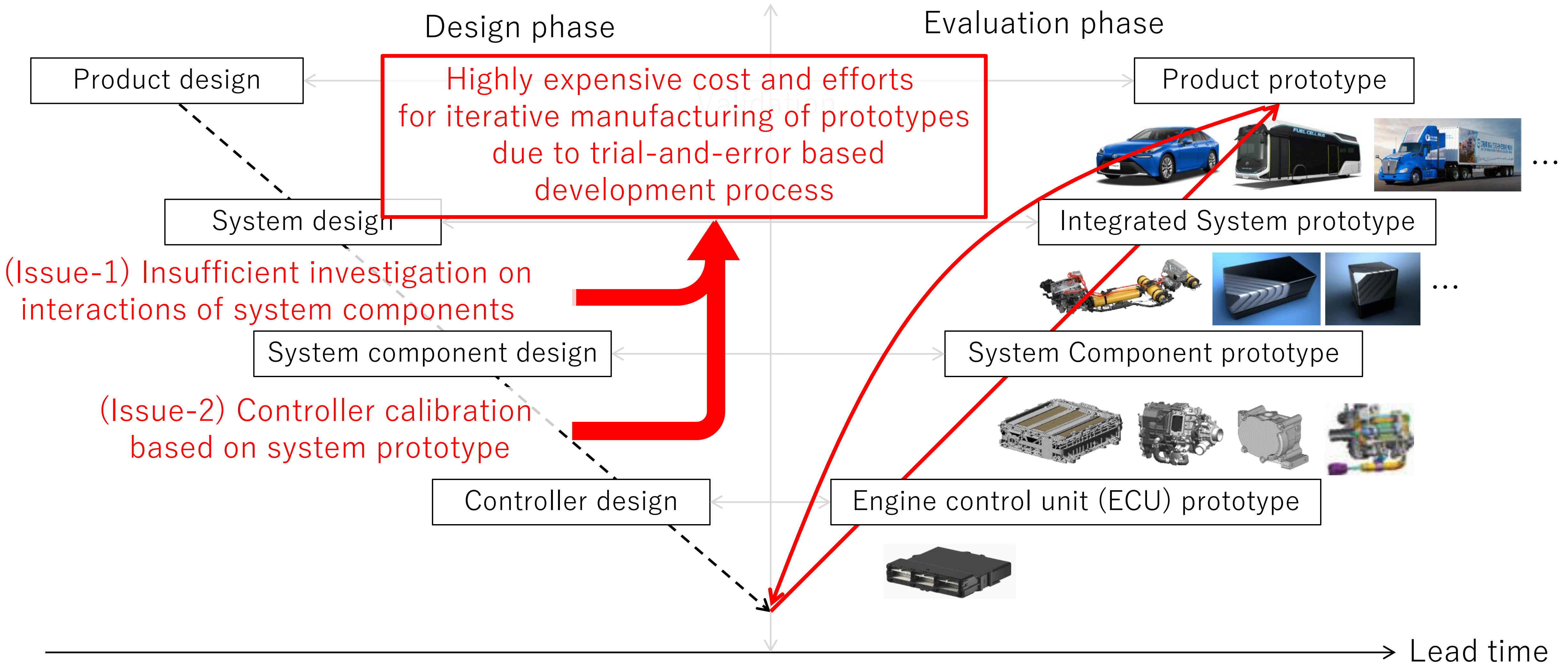
1. Background：Issues in FC system development process



Challenge

- Application of FC system to the various purpose for enhancement of H_2 utilization
- Development of multiple products in parallel with limited development resources

1. Background：Issues in FC system development process

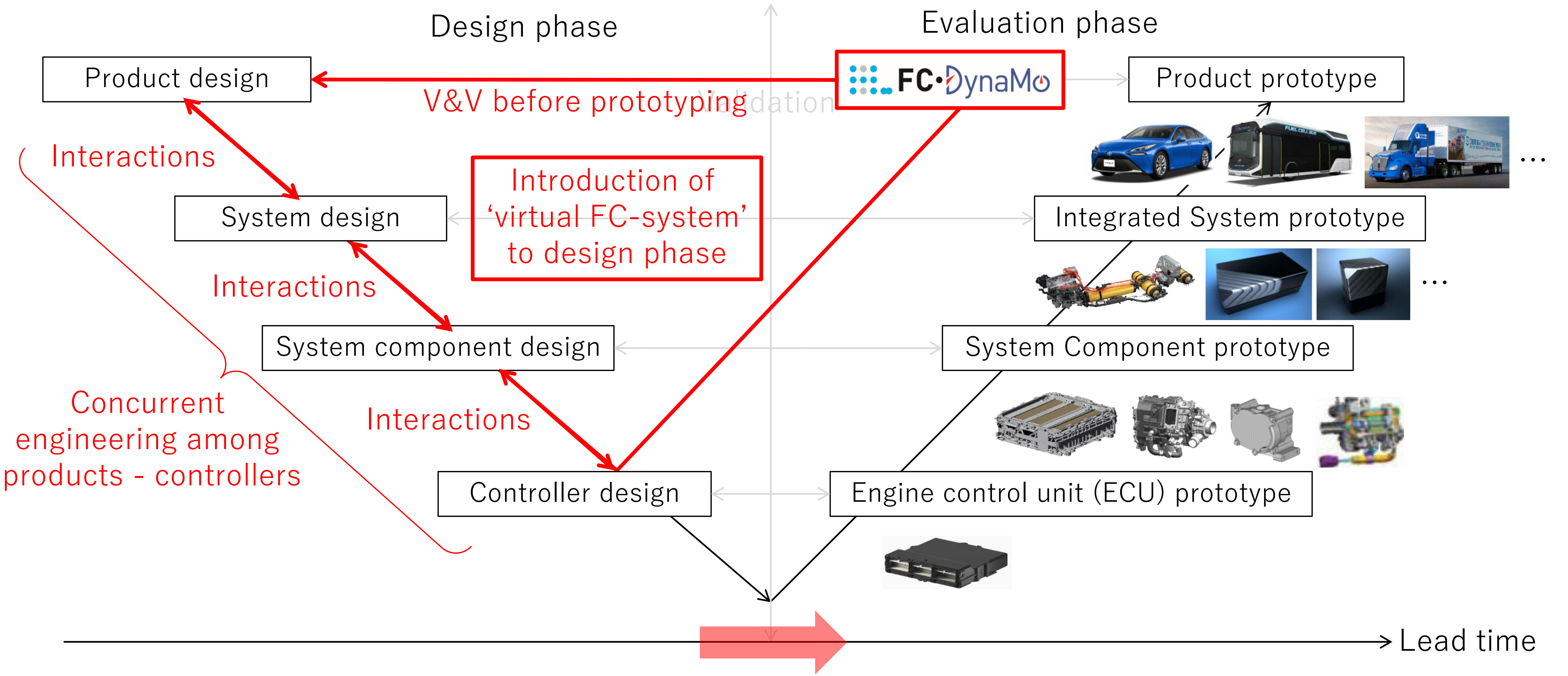


Issue

Highly expensive cost and effort required to trial-and-error based development process

→ One of the largest barriers to enter the fuel cell industry and enhancement of H_2 industry

1. Background：Issues in FC system development process

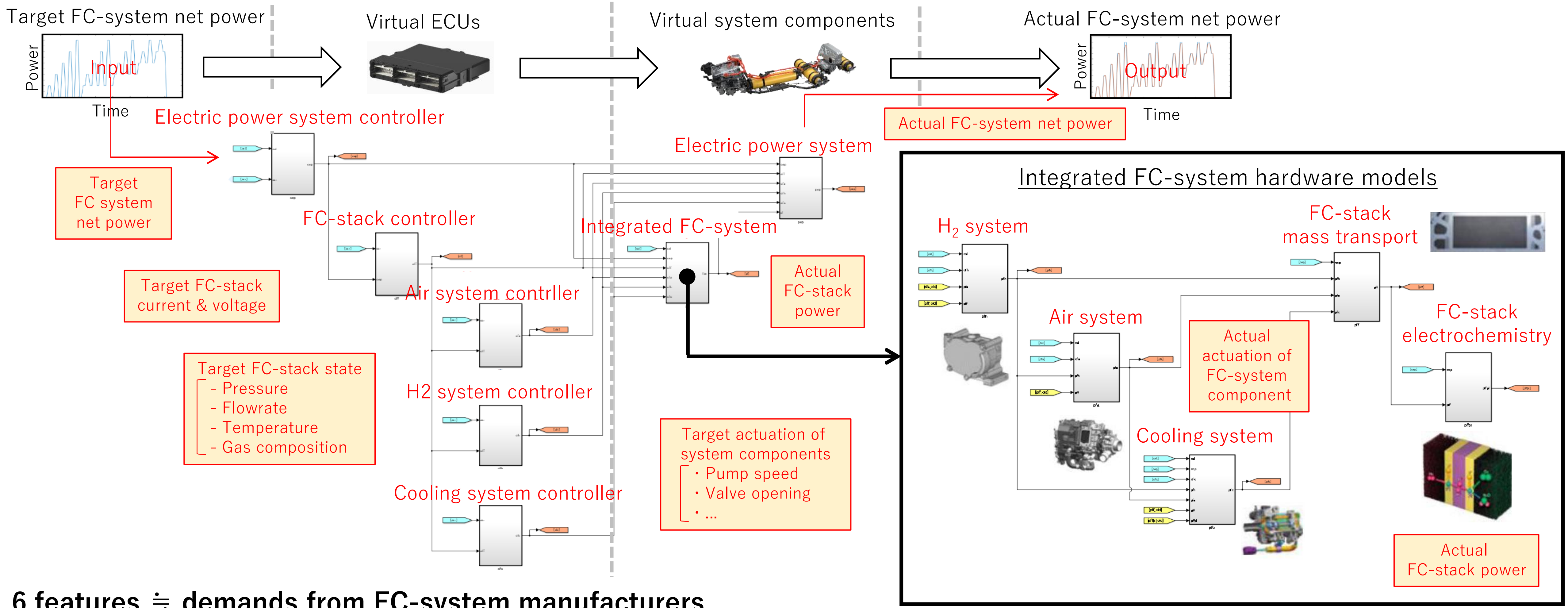


Prototypes with prospective goal achievement

Solution

Concurrent engineering of product, system, component, and controller design considering interaction of components and controllers by introducing 'virtual FC system' in design phase

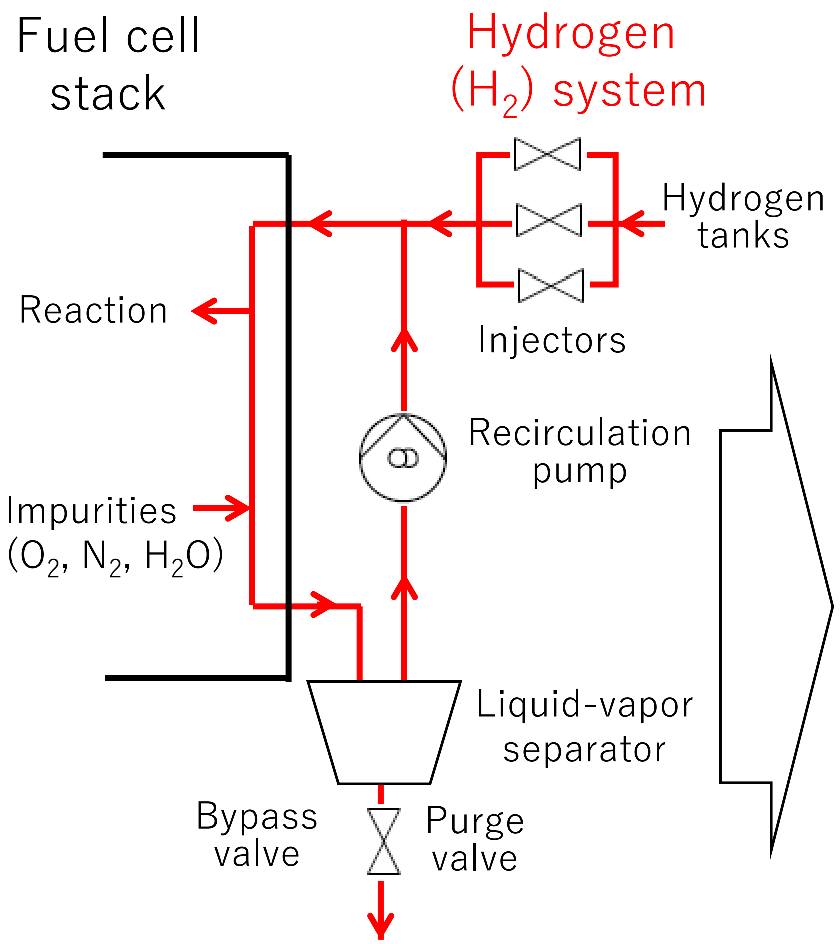
2. Integrated FC-system simulator

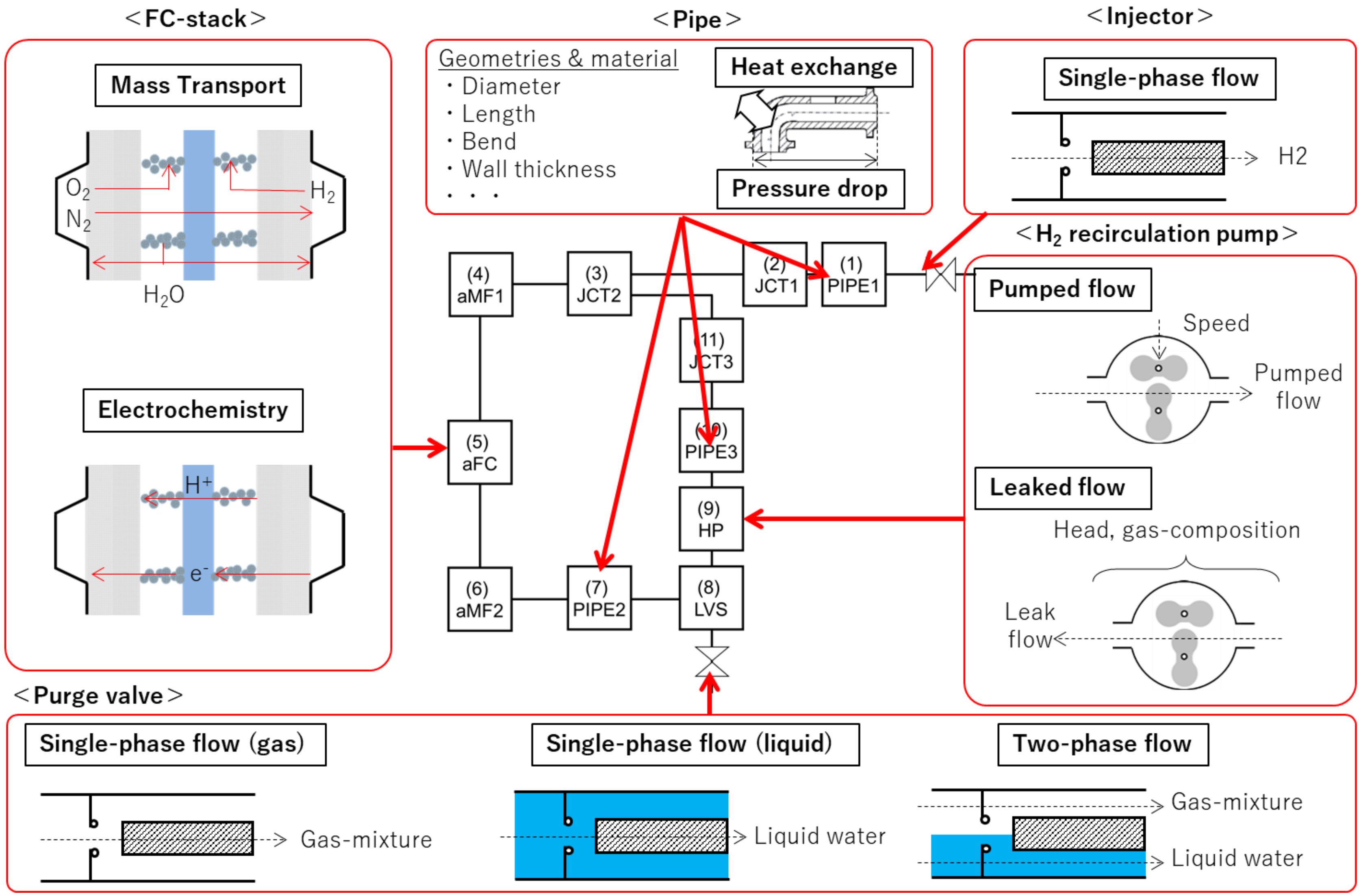


6 features ≒ demands from FC-system manufacturers

- Comprehensiveness : Physical models in system hardware & controllers in the entire system are included
- Multi-scale : Physics of m-scale system component & nm-scale FC-stack materials are included
- Dynamics : Dynamic system behaviors of an entire FC-system can be simulated
- Computational speed : x50 acceleration than the real time for the benefit of a year-long durability simulation purpose
- Accuracy : Validation and verification by the database collected with a commercial FCEV (Gen.2 MIRAI).
- Usability/Customizability : Implemented on MATLAB®/ Simulink® without additional toolboxes, all the codes are white-box

3. Physical modeling of FC-system : Modeling strategy



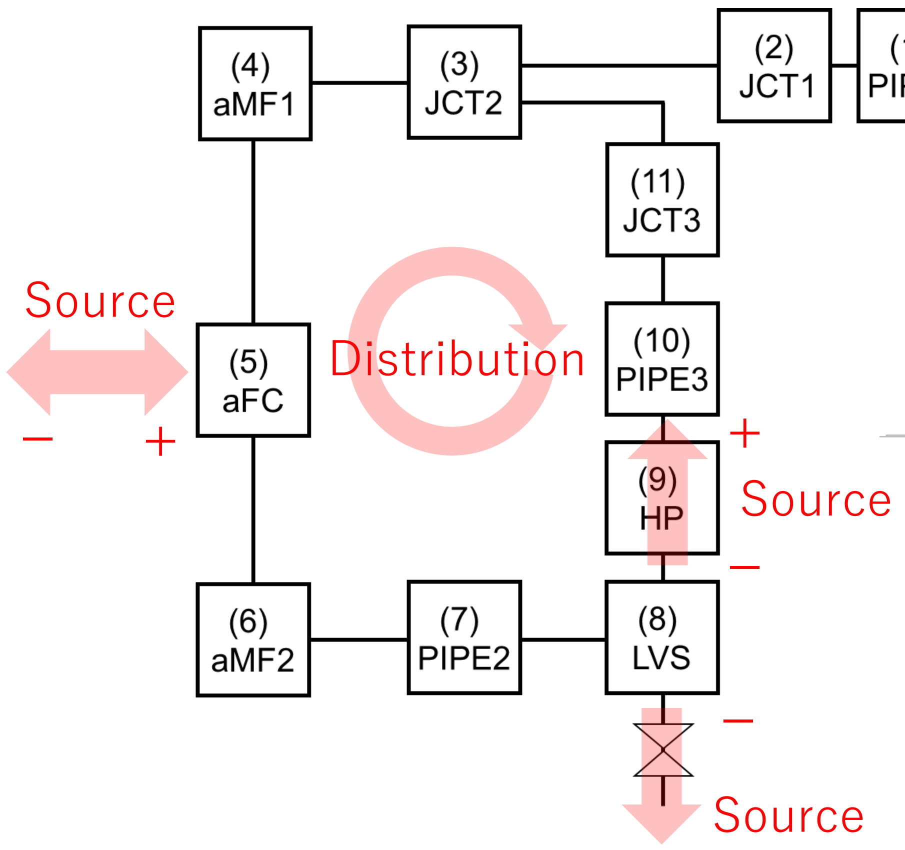


Function-block diagram

- Entire system is broken-down into component level, and expressed as connection of function-blocks
- State variables of pressure, flowrate, temperature, and gas composition across the system
- 1D physical models of mass-transport, electrochemistry in FC-stack and dynamics in system

3. Physical modeling of FC system : Numerical methods

Function block diagram



Linearization :
11-formula for
11-components

Algebraic equations

Mass balance
(Pressure)

$$
\begin{matrix} (1)\ \mathrm{PIPE1} \\ (2)\ \mathrm{JCT1} \\ (3)\ \mathrm{JCT2} \\ (4)\ \mathrm{aMF1} \\ (5)\ aFC \\ (6)\ aFC2 \\ (7)\ \mathrm{PIPE2} \\ (8)\ \mathrm{LVS} \\ (9)\ \mathrm{HP} \\ (10)\ \mathrm{PIPE3} \\ (11)\ \mathrm{JCT3} \end{matrix}
\begin{pmatrix} P_{tot}^{(1)} \\ P_{tot}^{(2)} \\ P_{tot}^{(3)} \\ P_{tot}^{(4)} \\ P_{tot}^{(5)} \\ P_{tot}^{(6)} \\ P_{tot}^{(7)} \\ P_{tot}^{(8)} \\ P_{tot}^{(9)} \\ P_{tot}^{(10)} \\ P_{tot}^{(11)} \end{pmatrix}
=
\begin{pmatrix}
a^{(1)(1)} & a^{(1)(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
a^{(2)(1)} & a^{(2)(2)} & a^{(2)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a^{(3)(2)} & a^{(3)(3)} & a^{(3)(4)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(3)(11)} \\
0 & 0 & a^{(4)(3)} & a^{(4)(4)} & a^{(4)(5)} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & a^{(5)(4)} & a^{(5)(5)} & a^{(5)(6)} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & a^{(6)(5)} & a^{(6)(6)} & a^{(6)(7)} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a^{(7)(6)} & a^{(7)(7)} & a^{(7)(8)} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a^{(8)(7)} & a^{(8)(7)} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a^{(9)(9)} & a^{(9)(10)} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a^{(10)(9)} & a^{(10)(10)} & a^{(10)(11)} \\
0 & 0 & a^{(11)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(11)(10)} & a^{(11)(11)}
\end{pmatrix}^{-1}
\begin{pmatrix} b^{(1)} \\ b^{(2)} \\ b^{(3)} \\ b^{(4)} \\ b^{(5)} \\ b^{(6)} \\ b^{(7)} \\ b^{(8)} \\ b^{(9)} \\ b^{(10)} \\ b^{(11)} \end{pmatrix}
$$

molar balance
(Concentration of O_2, H_2, N_2, and H_2O)

$$
\begin{matrix} (1)\ \mathrm{PIPE1} \\ (2)\ \mathrm{JCT1} \\ (3)\ \mathrm{JCT2} \\ (4)\ \mathrm{aMF1} \\ (5)\ aFC \\ (6)\ aFC2 \\ (7)\ \mathrm{PIPE2} \\ (8)\ \mathrm{LVS} \\ (9)\ \mathrm{HP} \\ (10)\ \mathrm{PIPE3} \\ (11)\ \mathrm{JCT3} \end{matrix}
\begin{pmatrix} P_i^{(1)} \\ P_i^{(2)} \\ P_i^{(3)} \\ P_i^{(4)} \\ P_i^{(5)} \\ P_i^{(6)} \\ P_i^{(7)} \\ P_i^{(8)} \\ P_i^{(9)} \\ P_i^{(10)} \\ P_i^{(12)} \end{pmatrix}
=
\begin{pmatrix}
a^{(1)(1)} & a^{(1)(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
a^{(2)(1)} & a^{(2)(2)} & a^{(2)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a^{(3)(2)} & a^{(3)(3)} & a^{(3)(4)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(3)(11)} \\
0 & 0 & a^{(4)(3)} & a^{(4)(4)} & a^{(4)(5)} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & a^{(5)(4)} & a^{(5)(5)} & a^{(5)(6)} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & a^{(6)(5)} & a^{(6)(6)} & a^{(6)(7)} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a^{(7)(6)} & a^{(7)(7)} & a^{(7)(8)} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a^{(8)(7)} & a^{(8)(7)} & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a^{(10)(9)} & a^{(10)(10)} & a^{(10)(11)} \\
0 & 0 & a^{(11)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(11)(10)} & a^{(11)(11)}
\end{pmatrix}^{-1}
\begin{pmatrix} b_i^{(1)} \\ b_i^{(2)} \\ b_i^{(3)} \\ b_i^{(4)} \\ b_i^{(5)} \\ b_i^{(6)} \\ b_i^{(7)} \\ b_i^{(8)} \\ b_i^{(9)} \\ b_i^{(10)} \\ b_i^{(11)} \end{pmatrix}
$$

Energy balance
(Temperature)

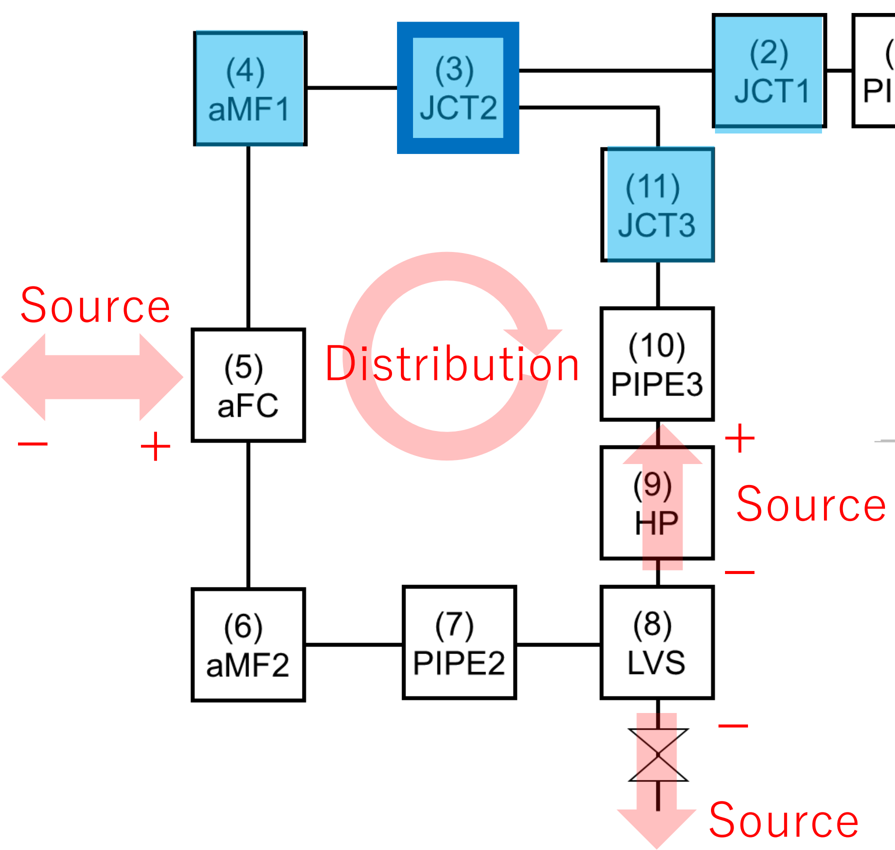
$$
\begin{matrix} (1)\ \mathrm{PIPE1} \\ (2)\ \mathrm{JCT1} \\ (3)\ \mathrm{JCT2} \\ (4)\ \mathrm{aMF1} \\ (5)\ aFC \\ (6)\ aFC2 \\ (7)\ \mathrm{PIPE2} \\ (8)\ \mathrm{LVS} \\ (9)\ \mathrm{HP} \\ (10)\ \mathrm{PIPE3} \\ (11)\ \mathrm{JCT3} \end{matrix}
\begin{pmatrix} T^{(1)} \\ T^{(2)} \\ T^{(3)} \\ T^{(4)} \\ T^{(5)} \\ T^{(6)} \\ T^{(7)} \\ T^{(8)} \\ T^{(9)} \\ T^{(10)} \\ T^{(11)} \end{pmatrix}
=
\begin{pmatrix}
a^{(1)(1)} & a^{(1)(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
a^{(2)(1)} & a^{(2)(2)} & a^{(2)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a^{(3)(2)} & a^{(3)(3)} & a^{(3)(4)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(3)(11)} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a^{(7)(6)} & a^{(7)(7)} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a^{(8)(7)} & a^{(8)(8)} & a^{(8)(9)} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & a^{(9)(8)} & a^{(9)(9)} & a^{(9)(10)} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a^{(10)(9)} & a^{(10)(10)} & a^{(10)(11)} \\
0 & 0 & a^{(11)(3)} & 0 & 0 & 0 & 0 & 0 & 0 & a^{(11)(10)} & a^{(11)(11)}
\end{pmatrix}^{-1}
\begin{pmatrix} b^{(1)} \\ b^{(2)} \\ b^{(3)} \\ T^{aFC1} \\ \dfrac{T^{aFC1} + T^{aFC1}}{2} \\ T^{aFC1} \\ b^{(7)} \\ b^{(8)} \\ b^{(9)} \\ b^{(10)} \\ b^{(11)} \end{pmatrix}
$$

Features

- Algebraic equations to describe mass balance, molar balance, and energy balance in system
- ‘How the source term affects the distribution in one time step ?’ is expressed in each equation
- In-house and white-box numerical solvers for future improvement and customization

3. Physical modeling of FC system : Numerical methods

Function block diagram



Linearization :
11-formula for
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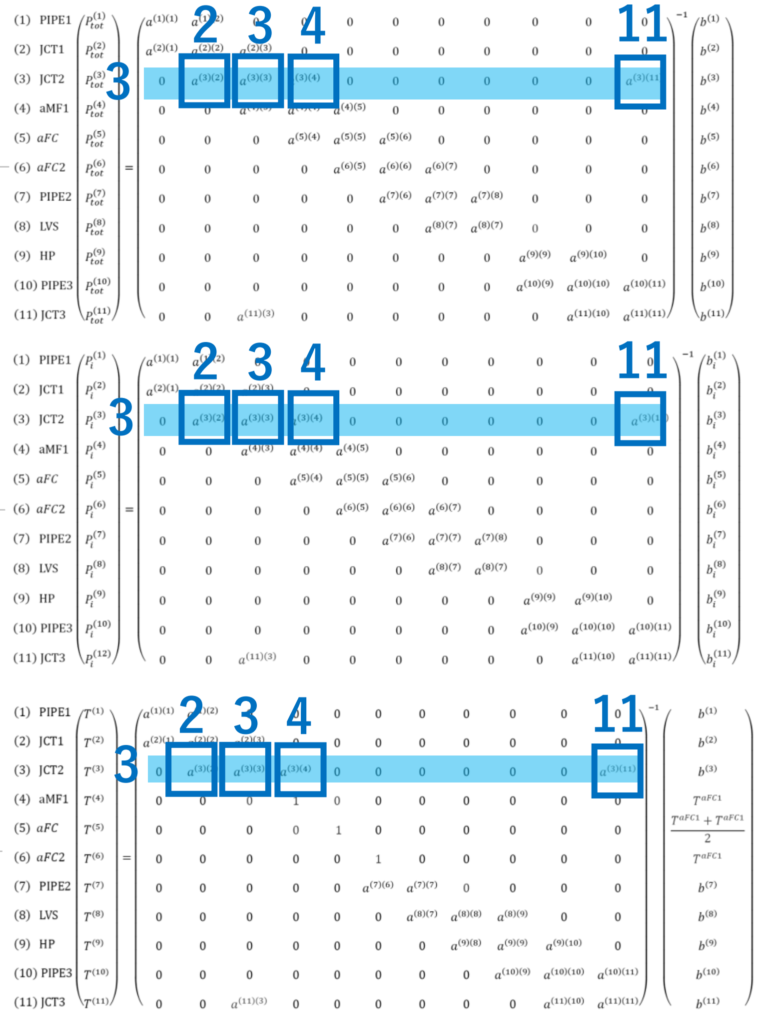
Algebraic equations

Mass balance (Pressure)

molar balance (Concentration of O_2, H_2, N_2, and H_2O)

Energy balance (Temperature)



Features

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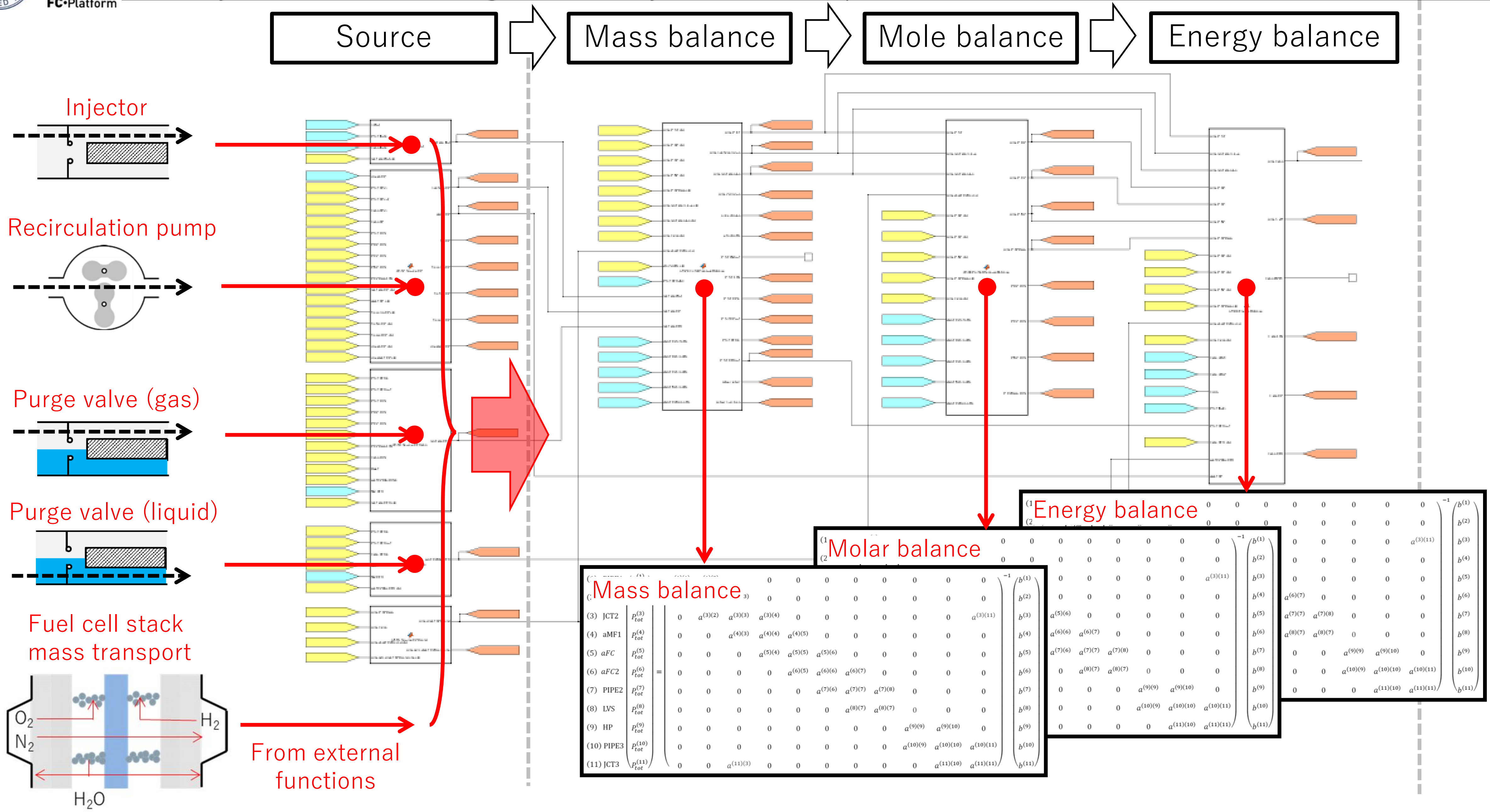
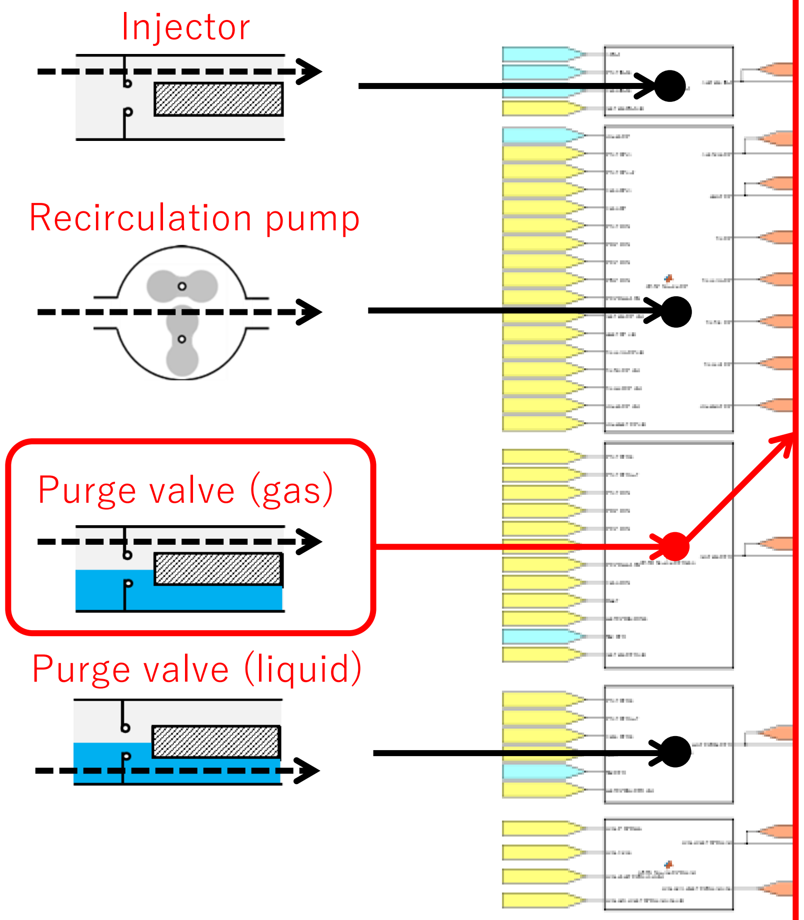


3. Physical modeling of FC system : Implementation to MATLAB/Simulink

Source ⇒ Mass balance ⇒ Mole balance ⇒ Energy balance



Spec-book

if $\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}} < \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \cong 0.5283$, $\dot{m}^{HEV}_{gas} = A^{eff}_{HEV}\frac{P^{HEVin}_{tot}}{\sqrt{R^{HEVin}_{gas}T^{HEVin}_{gas}}}\sqrt{\left(\frac{2\gamma}{\gamma-1}\right)\left[\left\{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right\}^{\frac{2}{\gamma}} - \left\{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right\}^{\frac{\gamma+1}{\gamma}}\right]}$

else $\dot{m}^{HEV}_{gas} = A^{eff}_{HEV}\frac{P^{HEVin}_{tot}}{\sqrt{R^{HEVin}_{gas}T^{HEVin}_{gas}}}\sqrt{\left(\frac{2\gamma}{\gamma-1}\right)\left[\left(\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}}\right)^{\frac{2}{\gamma}} - \left(\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}}\right)^{\frac{\gamma+1}{\gamma}}\right]}$

⇓

Implementation

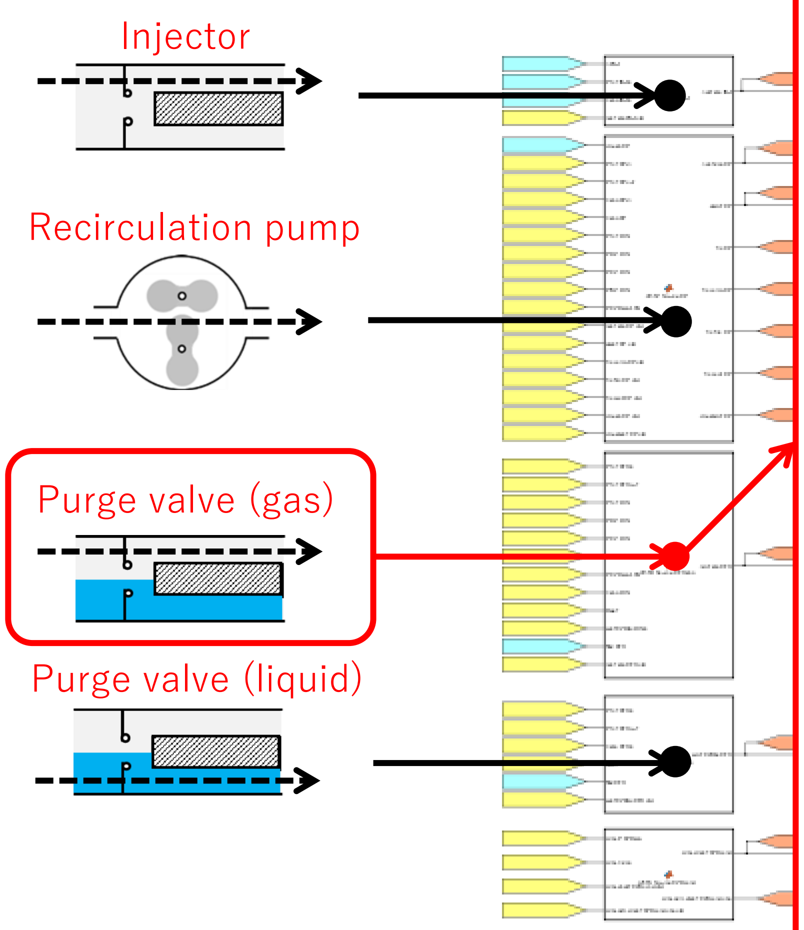
```
% Choked flow
if P_out/P_in < (2/(gamma_gas+1))^(gamma_gas/(gamma_gas-1))
    % Mass-flowrate at HEV [mol/min]
    mdot = A_HEV                                                        ...
           * eta_HEV_gas1                                               ...
           * eta_HEV_gas2                                               ...
           * (P_in/sqrt(R_gas * T_in))                                  ...
           * sqrt(2*gamma_gas/(gamma_gas-1))                            ...
           * sqrt(((2/(gamma_gas+1))^(gamma_gas/(gamma_gas-1)))^(2/gamma_gas)   ...
             - ((2/(gamma_gas+1))^(gamma_gas/(gamma_gas-1)))^((gamma_gas+1)/gamma_gas));Q
% Subsonic flow
elseif ((2/(gamma_gas+1))^(gamma_gas/(gamma_gas-1)) <= P_out/P_in) && (P_out/P_in < 1)

    % Mass-flowrate at HEV [mol/min]
    mdot = A_HEV                                                        ...
           * eta_HEV_gas1                                               ...
           * eta_HEV_gas2                                               ...
           * (P_in/sqrt(R_gas * T_in))                                  ...
           * sqrt(2*gamma_gas/(gamma_gas-1))                            ...
           * sqrt((P_out/P_in)^(2/gamma_gas) - (P_out/P_in)^((gamma_gas+1)/gamma_gas));
```

‘Hybrid-coding’ = Physics in MATLAB + Interaction among physics in Simulink for the benefit of the effort and lead time of coding and reviewing

3. Physical modeling of FC system : Implementation to MATLAB/Simulink

Source ⇨ Mass balance ⇨ Mole balance ⇨ Energy balance



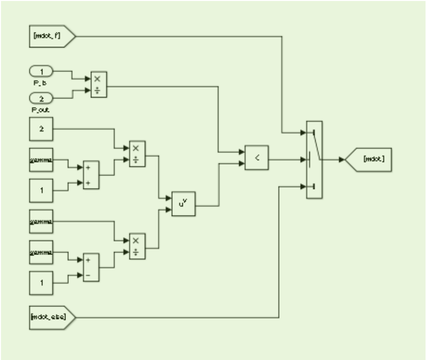
Spec-book

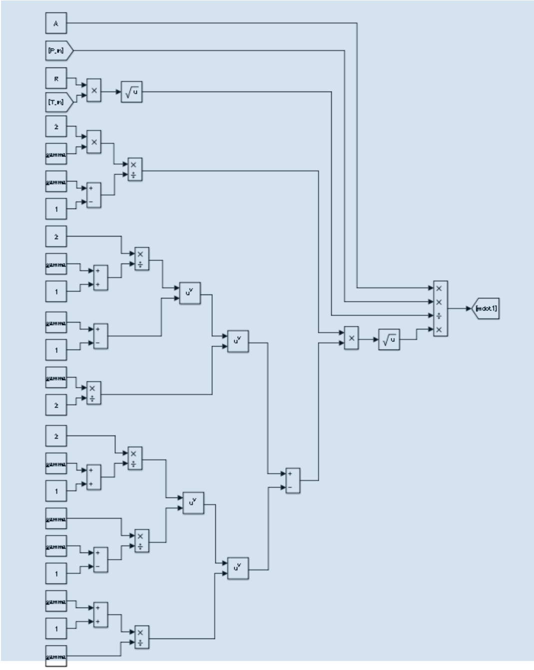
⇩

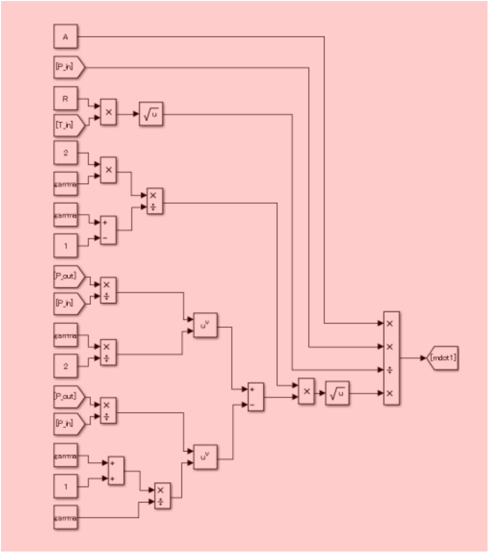
Implementation (Simulink)

if $\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}} < \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \cong 0.5283$, $\dot{m}^{HEV}_{gas} = A^{eff}_{HEV}\frac{P^{HEVin}_{tot}}{\sqrt{R^{HEVin}_{gas}T^{HEVin}_{gas}}}\sqrt{\left(\frac{2\gamma}{\gamma-1}\right)\left[\left\{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right\}^{\frac{2}{\gamma}} - \left\{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right\}^{\frac{\gamma+1}{\gamma}}\right]}$

else $\dot{m}^{HEV}_{gas} = A^{eff}_{HEV}\frac{P^{HEVin}_{tot}}{\sqrt{R^{HEVin}_{gas}T^{HEVin}_{gas}}}\sqrt{\left(\frac{2\gamma}{\gamma-1}\right)\left[\left(\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}}\right)^{\frac{2}{\gamma}} - \left(\frac{P^{HEVout}_{tot}}{P^{HEVin}_{tot}}\right)^{\frac{\gamma+1}{\gamma}}\right]}$



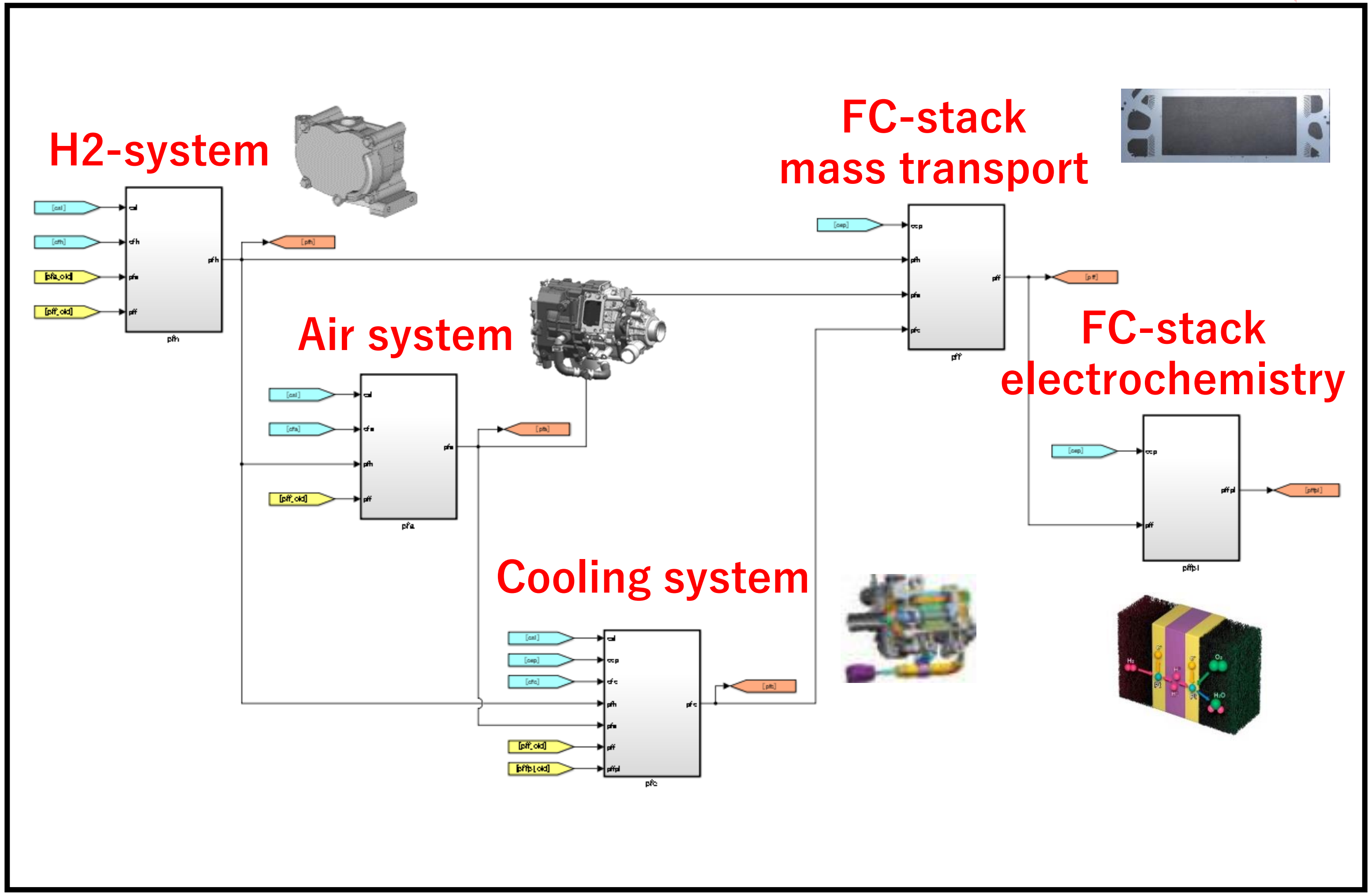


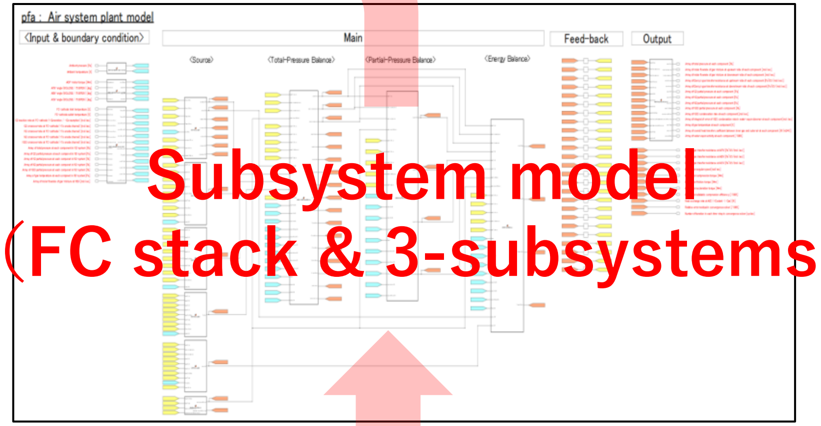


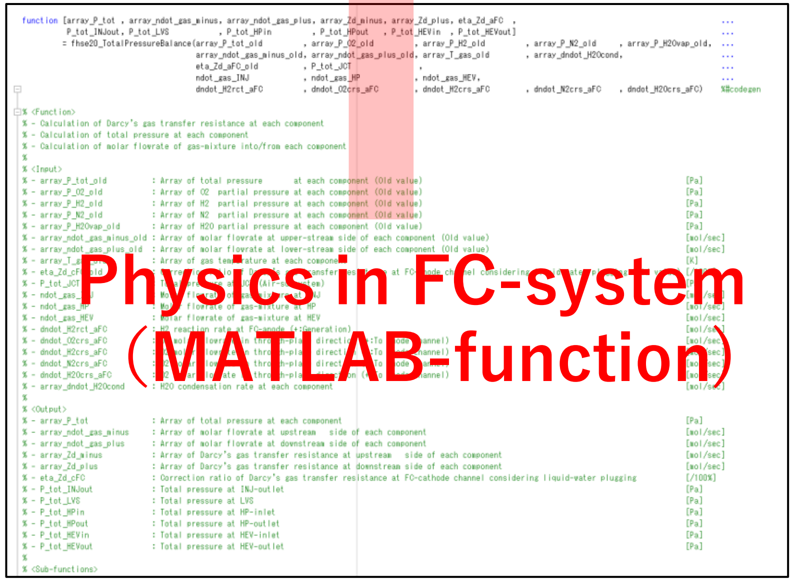
'Hybrid-coding' = Physics in MATLAB + Interaction among physics in Simulink for the benefit of the effort and lead time of coding and reviewing

3. Physical modeling of FC system : Implementation to MATLAB/Simulink

Integrated FC system hardware model



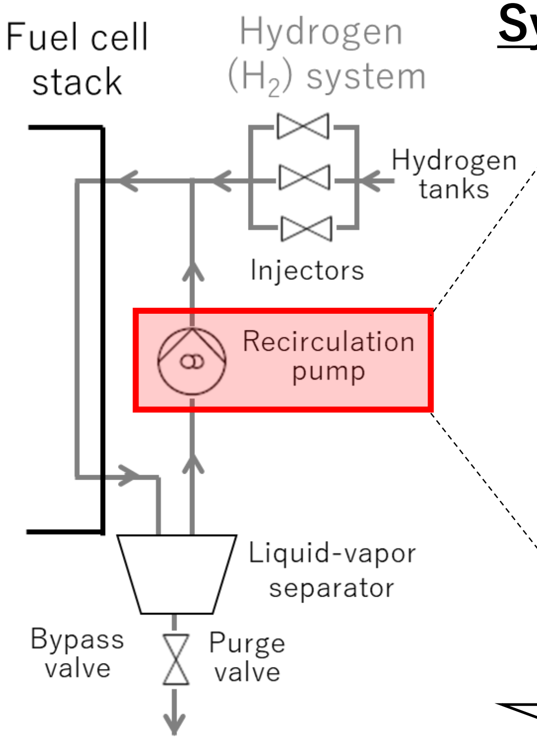


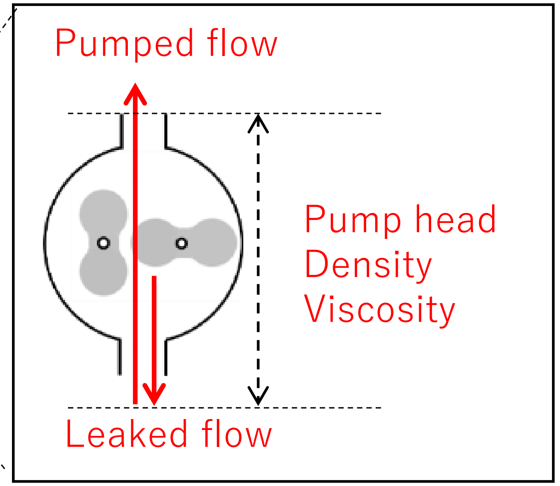


Individual physical model of FC stack and subsystems are integrated to an entire FC system model

3. Parameters determination : FC system component models

System component





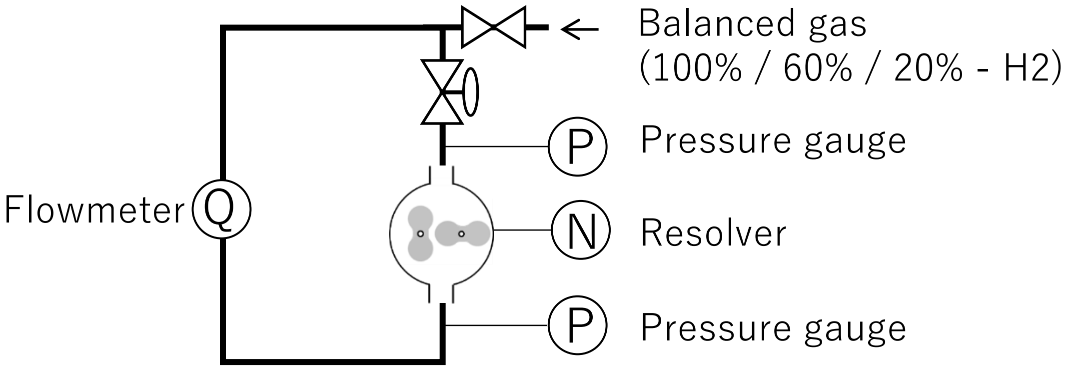
1D system component model

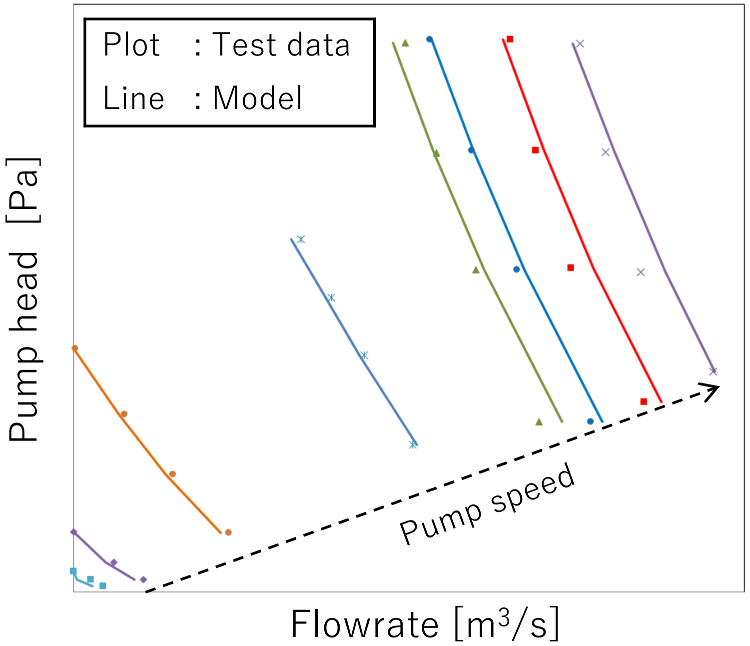
$$\dot{v} = C_1 N - C_2 \frac{\Delta P^{C_3}}{\mu^{C_4} \rho^{C_5}}$$

Overall flowrate; Pump speed; Pump head; Viscosity; Density

Calibration of C_1-C_5

Unit test data (NOT system data)

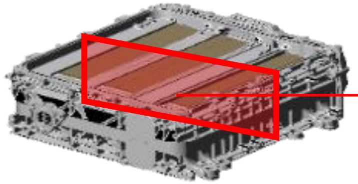




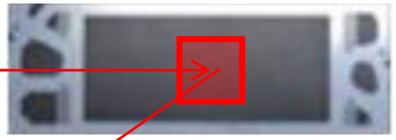
All the parameters can be determined with unit-test data (NOT system test data)

3. Parameters determination : FC stack models

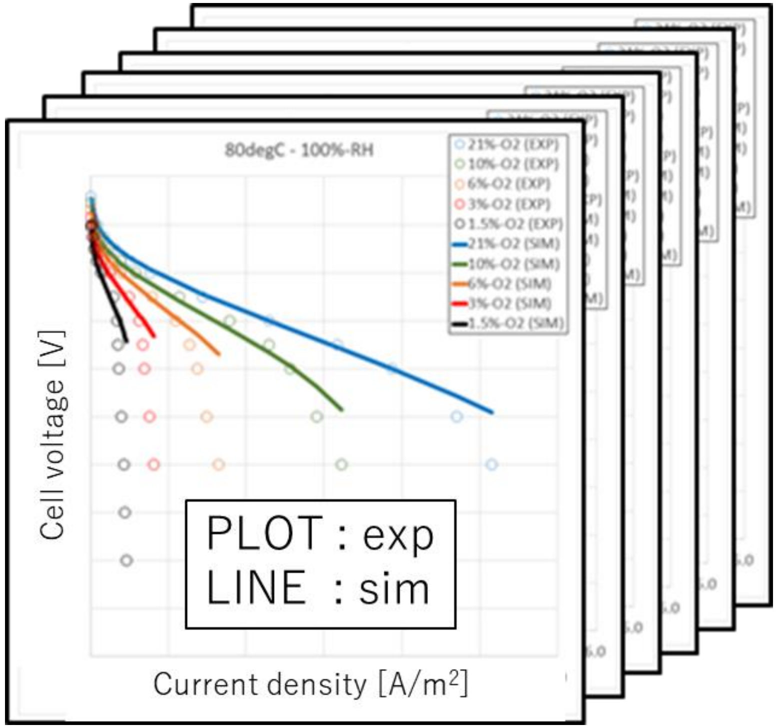
FC stack



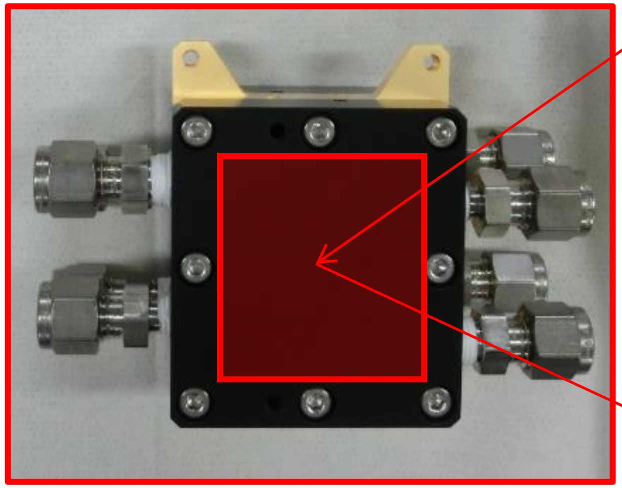
Single cell (≒ 300 cm^2)

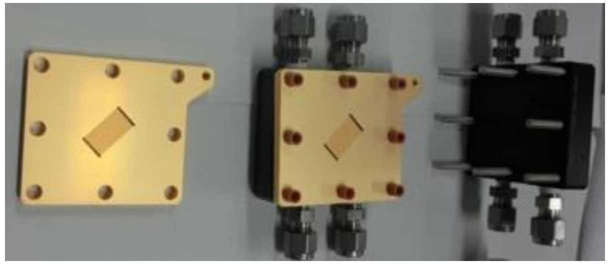


Experimental data

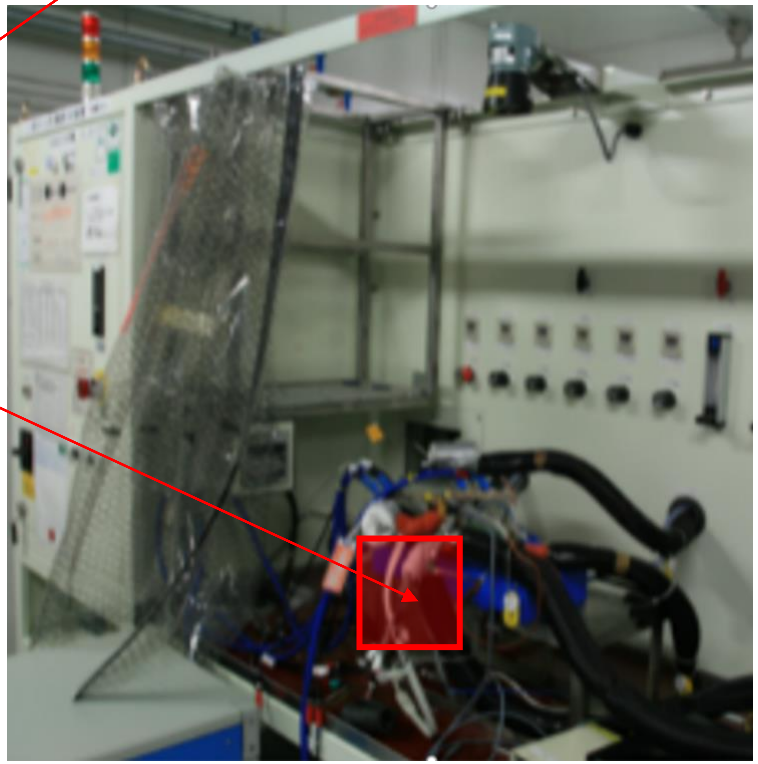


Test piece (1cm^2)





Test bed



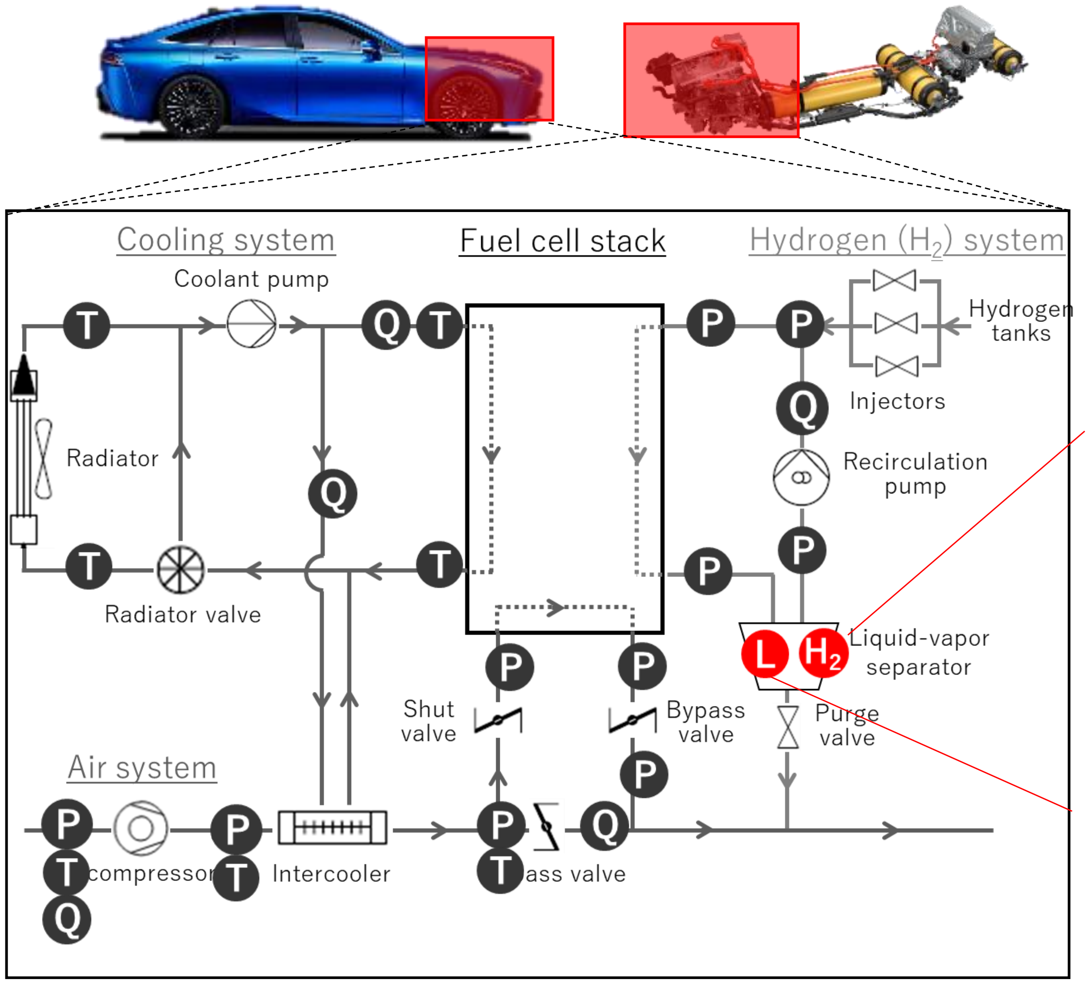
Boundary condition of 1cm^2-cell

- 5 humidity (100, 80, 60, 40, 20%)
- 5 O_2 concentration (21, 10, 6, 3, 1%)
- 3 coolant temperature (80 + 40, 60 °C)

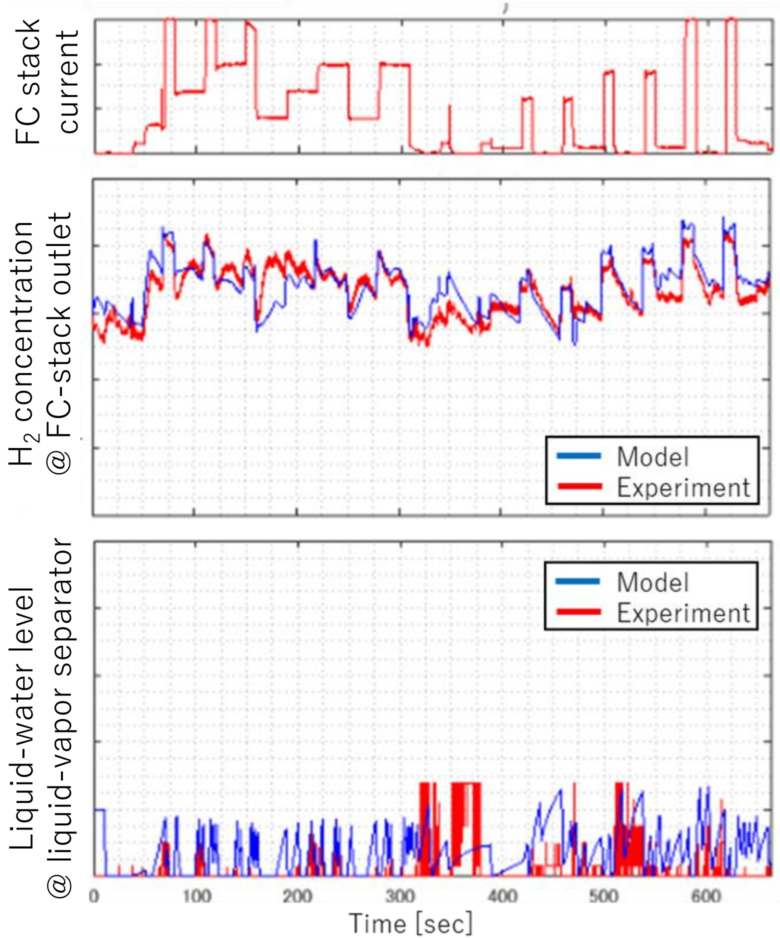
All the parameters can be determined with 1cm^2-cell data
and microscopic observations of material geometries (NOT cell/stack data)

4. Model validation & verification

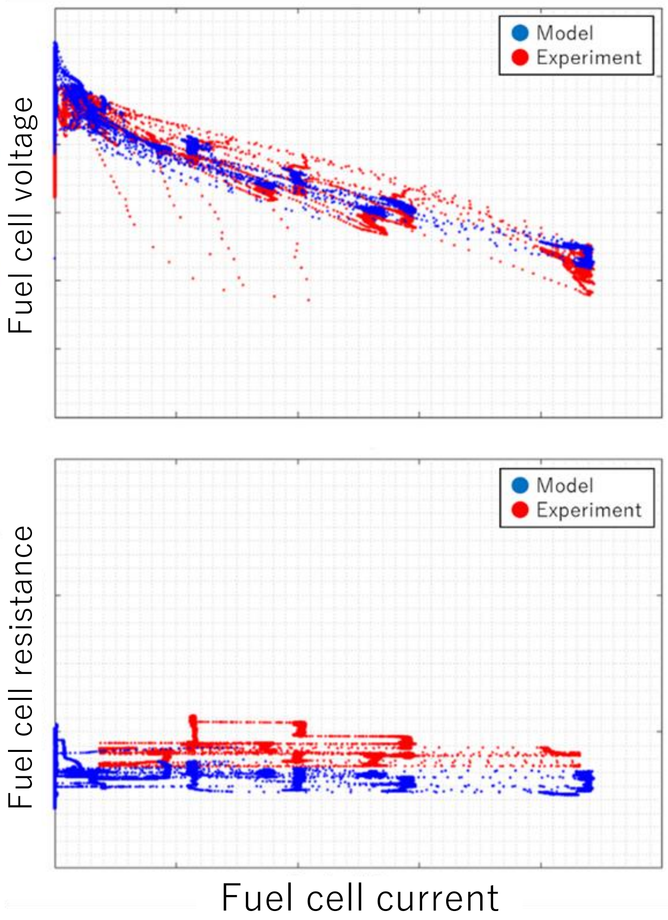
Prototype vehicle & system testbed
w/additional sensors for validation



System dynamics (H_2 system)



FC stack dynamics



Validated with the database collected with prototype vehicle
in wide range of conditions under low to high load and temperature

5. Simulation results : System dynamics in an entire FC-system

(Input) Target FC-system net power

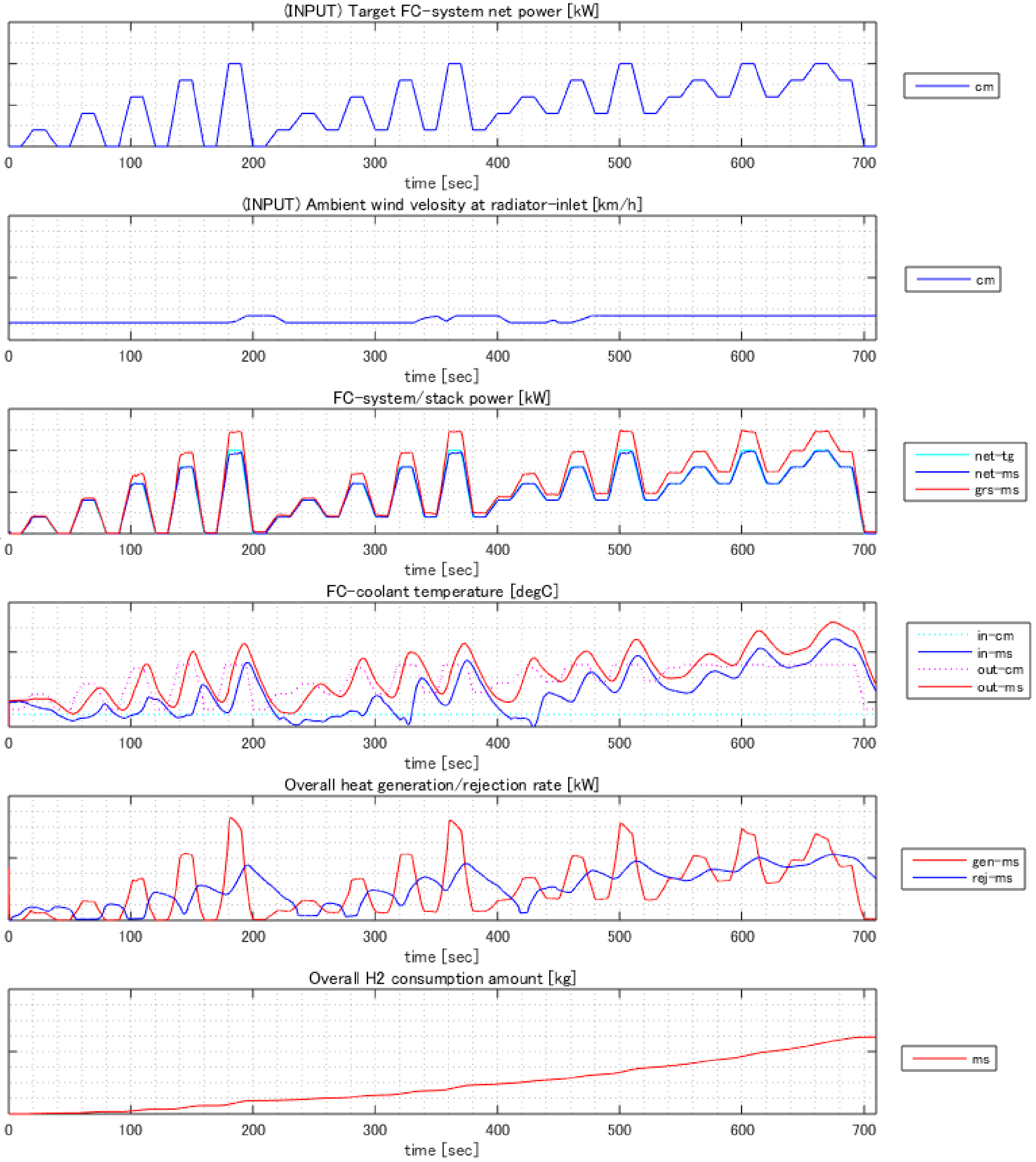
(Input) Wind velocity at radiator inlet

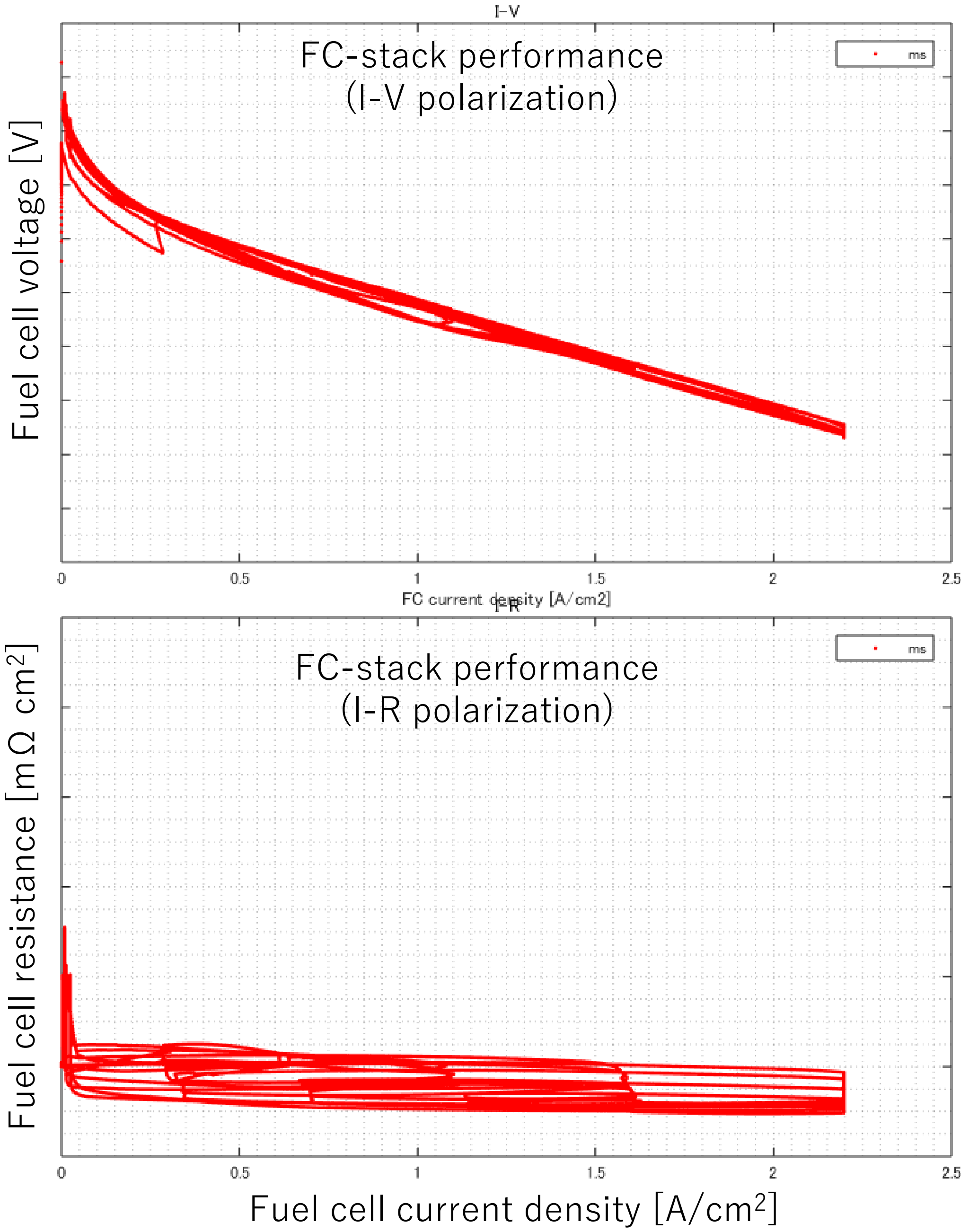
Target tracking performance / FC gross power

Coolant temperature at FC-inlet/outlet

Heat generation / emission rate in FC-system

Accumulated H_2 consumption amount





5. Simulation results : Computational speed

Summary of computational speed

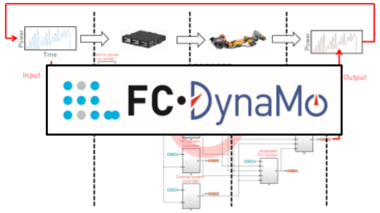
Hardware	CPU	Intel® Xeon® CPU E3-1230 v5 @ 3.40GHz, 3.41GHz
	RAM	8.00 GB
Software	OS	Windows 10® Enterprise
	MATLAB®	R2015a (8.5.0.197613)
	SIMULINK®	Version 8.5 (R2015a)

Experimental data	Total time	700 sec
	Number of data	42724 time-steps (0.016384 sec/step)
Computational time		13.2 sec

> 50 times faster than real-time

Capability of year-long durability simulation in allowable computational time

Future work : Road map of FC-DynaMo development

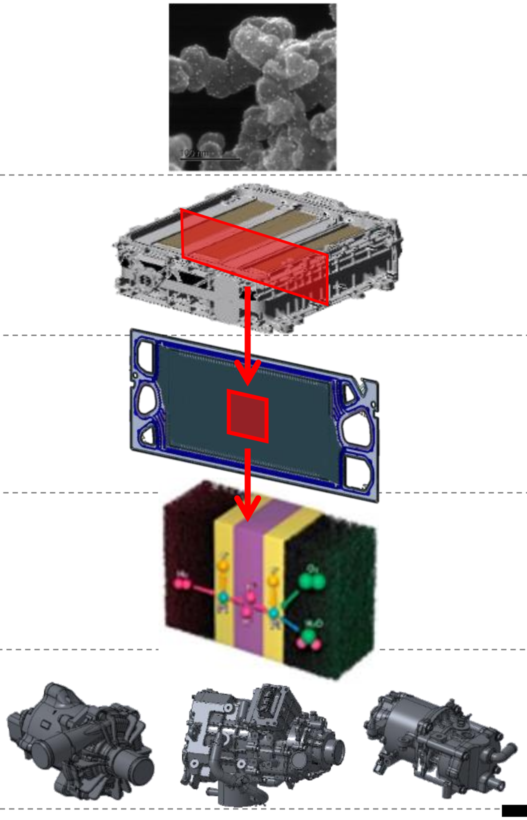


Being delivered to Japanese FCS manufacturers

- Year-1
- Year-2
- Year-3

Hardware models

Controllers



GUI

Target of Year-2 and 3

FC-stack (degradation)

- Catalyst (platinum)
- Catalyst (carbon)
- Membrane (chemical)
- Membrane (Mechanical)

FC-stack (degradation avoidance)

- Catalyst (platinum)
- Catalyst (carbon)
- Membrane (chemical)
- Membrane (Mechanical)

FC-stack (1+1+1D : stacking direction)

- Mass transport
- Electrochemistry

FC-stack (1+1D : In-plant direction)

- Mass transport
- Electrochemistry

FC-stack (1D : Through-plane direction)

- Mass transport
- Electrochemistry

FC-stack

- Power
- Fuel economy
- Cooling

FC-system

- Air
- H2
- Cooling
- Electric power

FC-system

- Air
- H2
- Cooling
- Electric power

Platform : MATLAB SIMULINK

Core interests of Year-2 & 3 : Development of Models for distribution across FC-stack & FC material degradation

For detailed information

Sep. 2022

Modeling of
overall fuel cell system
dynamics

ECS Transactions

Modeling of the dynamic behavior of an integrated fuel cell system including fuel cell stack, air system, hydrogen system, and cooling system

Shigeki Hasegawa[1], Yoshihiro Ikogi[2], Sanghong Kim[3], Miho Kageyama[4] and Motoaki Kawase[4]

ECS Transactions, Volume 109, Number 9

Citation Shigeki Hasegawa *et al* 2022 *ECS Trans.* **109** 15

Sep. 2021

Modeling of
fuel cell stack
dynamics

ECS Transactions

Modeling of Fuel Cell Stack for High-Speed Computation and Implementation to Integrated System Model

Shigeki Hasegawa[1,2], Motoyuki Kimata[3], Yoshihiro Ikogi[1], Miho Kageyama[2], Motoaki Kawase[2] and Sanghong Kim[4]

ECS Transactions, Volume 104, Number 8

Citation Shigeki Hasegawa *et al* 2021 *ECS Trans.* **104** 3

Conclusions

1D physical model for integrated fuel cell system, FC·DynaMo as developed to enable year-long simulation of an entire fuel cell system dynamics in allowable calculation time

Accomplishments

- Function-block modeling & implementation methods
- Parameter determination process without collecting system-scale data
- x50 computational time than real time
- Validation by the database collected with commercial FCEV

Future work

- Implementation of degradation models of FC materials for HDV application
- Extension of FC stack models to 1+1D and 1+1+1D directions

Acknowledgement

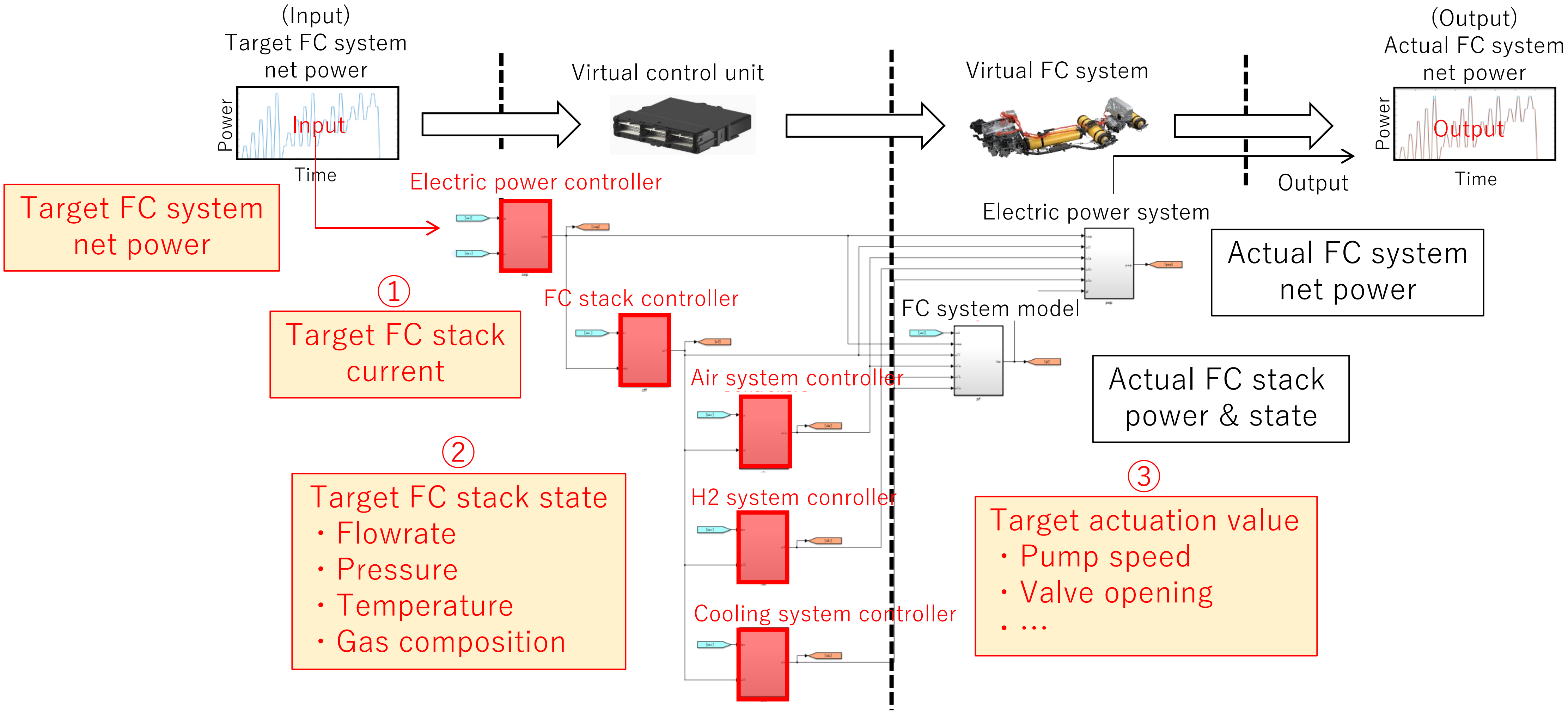
FC·Platform

Development of design-for-purpose numerical simulators for attaining long life and high performance project (FY2020 - 2023),
New Energy and Industrial Technology Development Organization (NEDO), Japan

Appendix

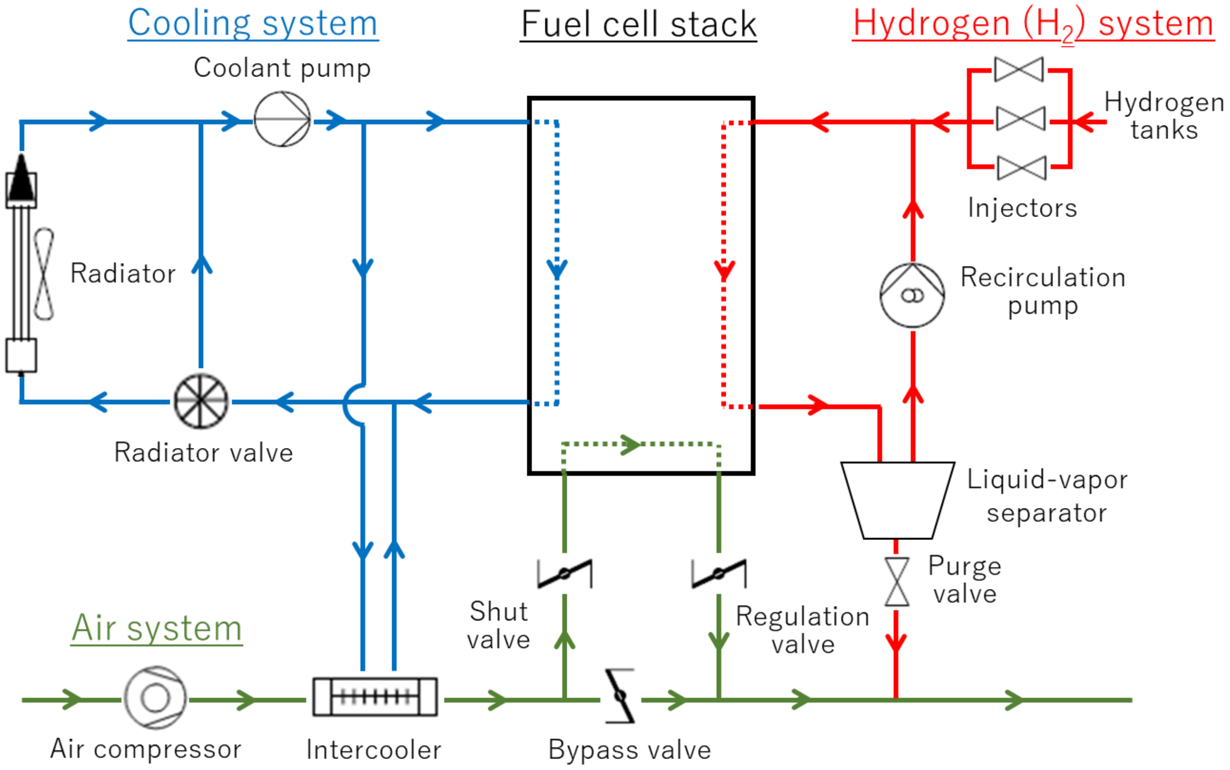
Controllers : Overview

3-step controller architecture, convertion of target power → state → actuation value
‘LEGO-BLOCK’ implementation for separation of calibration process and easy implementation



Controllers : Overview

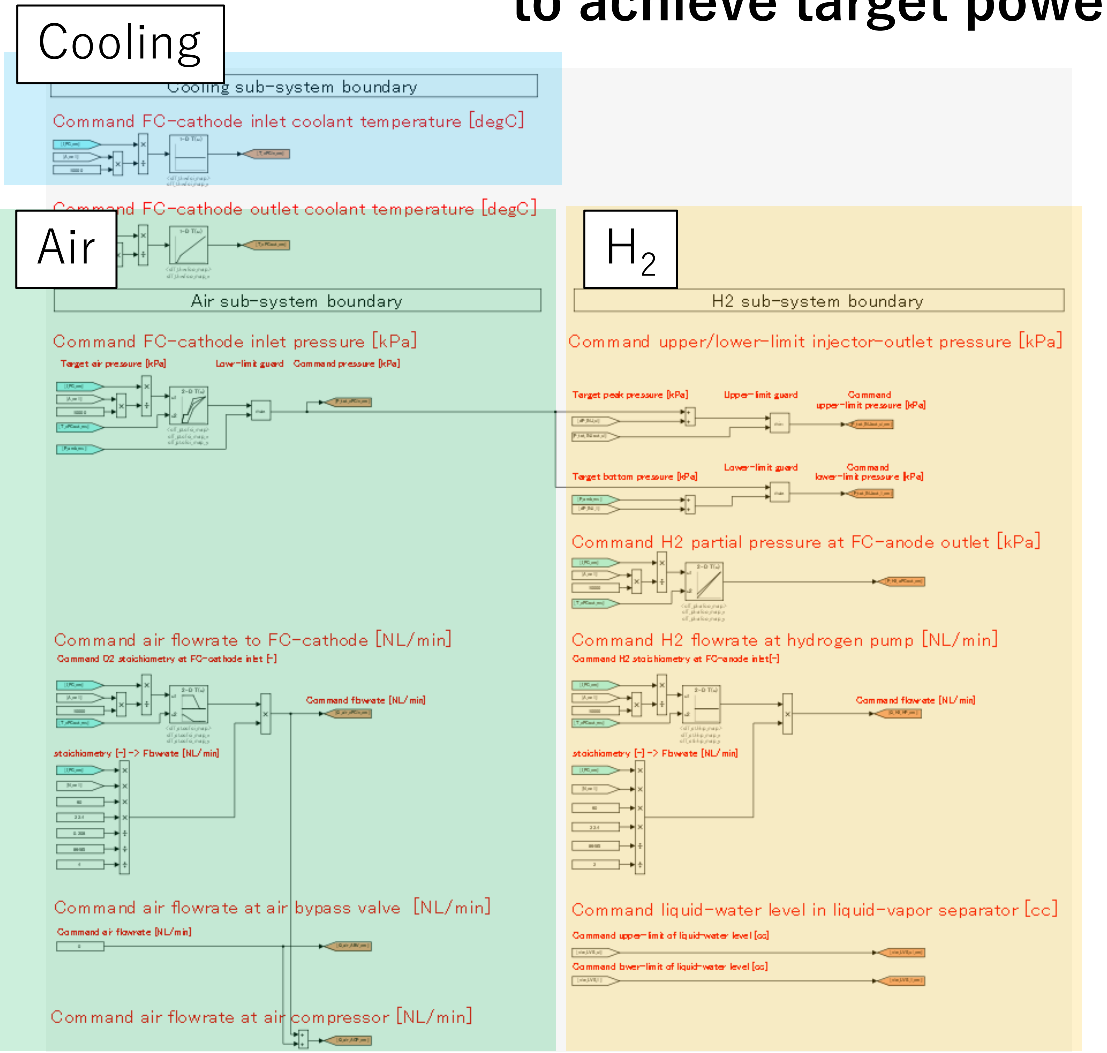
Role of each system component defined
to achieve target power tracking in high FC system efficiency



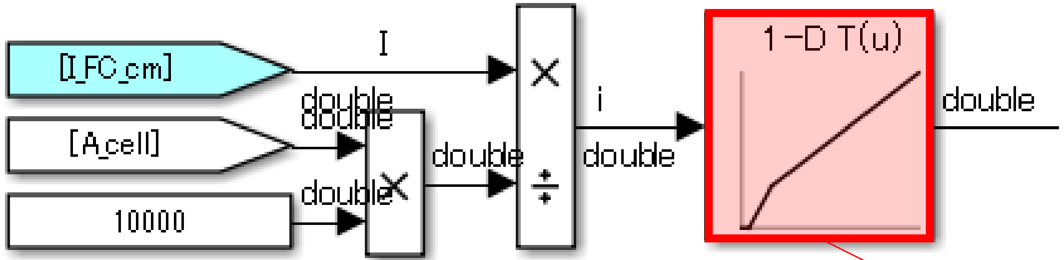
	ユニット	制御対象
Air	Air compressor	Total air flowrate
	Regulation valve	Air pressure
	Bypass valve	Bypass air flowrate
	Shut valve	Sealing in shut-down condition
H_2	Injector	H_2 partial pressure
	Purge valve	H_2 partial pressure
	Recirculation valve	Circulation flowrate
	Liquid-vapor separator	Removal of water droplets
Cooling	Coolant pump	FC stack outlet temperature
	Radiator valve	FC stack inlet temperature
	Radiator + fan	Boosting radiator performance

Controllers : FC stack controller

Optimized FC stack boundary condition of flowrate, pressure, temperature, and composition to achieve target power tracking in high system efficiency



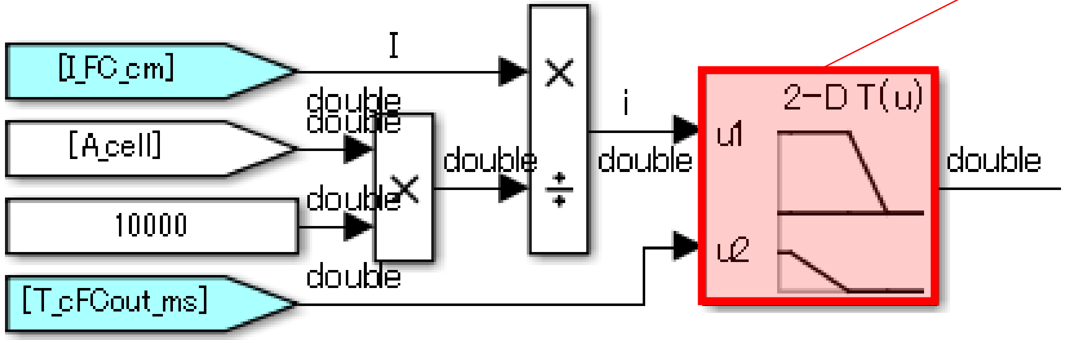
(Ex：Cooling) Target coolant temperature



Input：FC current

Predetermined functions

(Ex：Air) Target air flowrate



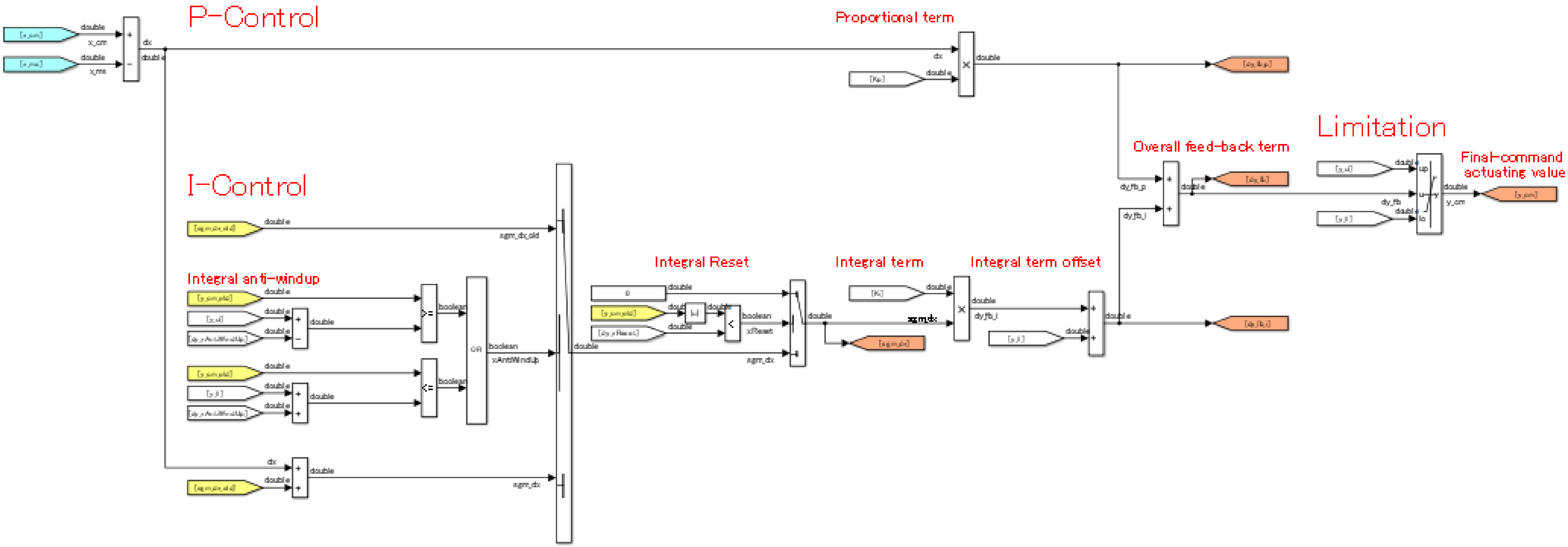
Input：FC current ＋temperature

- Operating conditions are calibrated and implemented as table data
- Separation of FC stack & components controller calibration process ('LEGO-BLOCK' implementation)

Controllers : FC system component controller

(Ex : Air) Air compressor speed controller

Input : Target flowrate → Output : Target speed

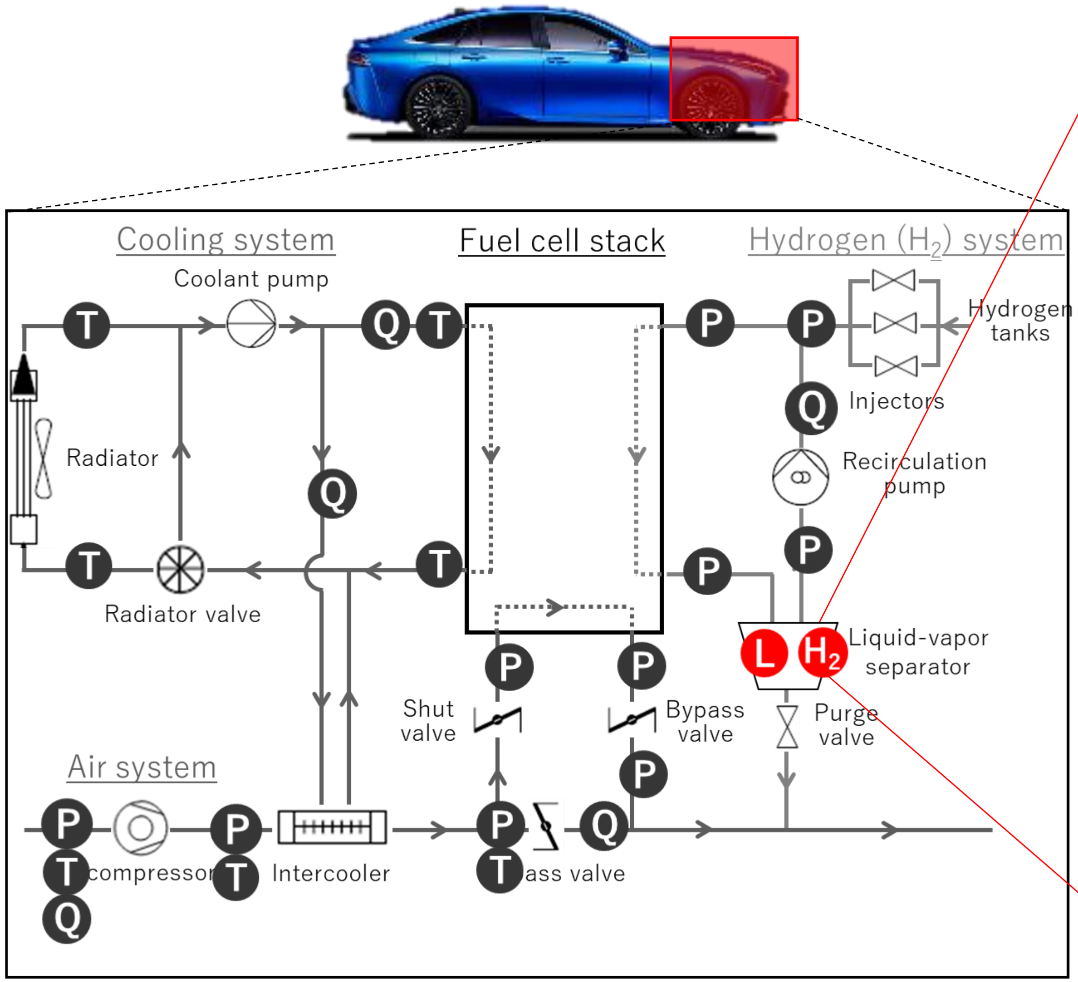


- Simple SISO PI controller, various component characteristics can be expressed by only PI gain tuning
- More sophisticated controller such as MPC can be implemented by replacing original controller without large effort (‘LEGO-BLOCK’ implantation)

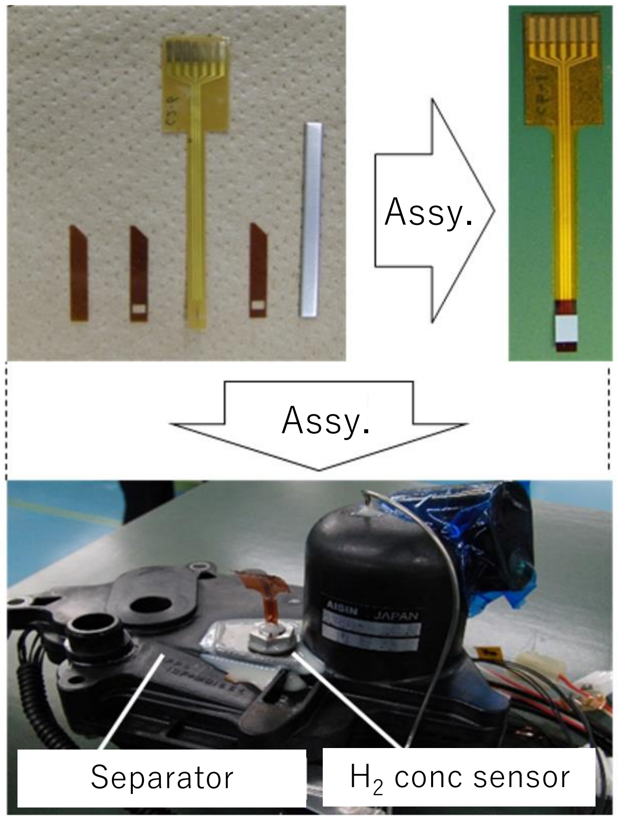
Model validation

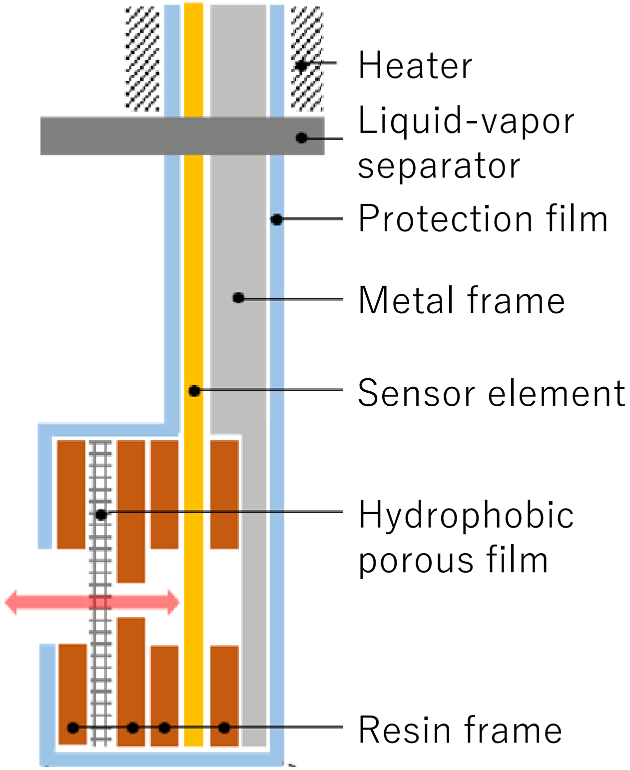
Following the packaging limitation to install additional sensors, compact and accurate sensors were newly developed

Prototype vehicle
w/additional sensors for validation



H_2 concentration sensor





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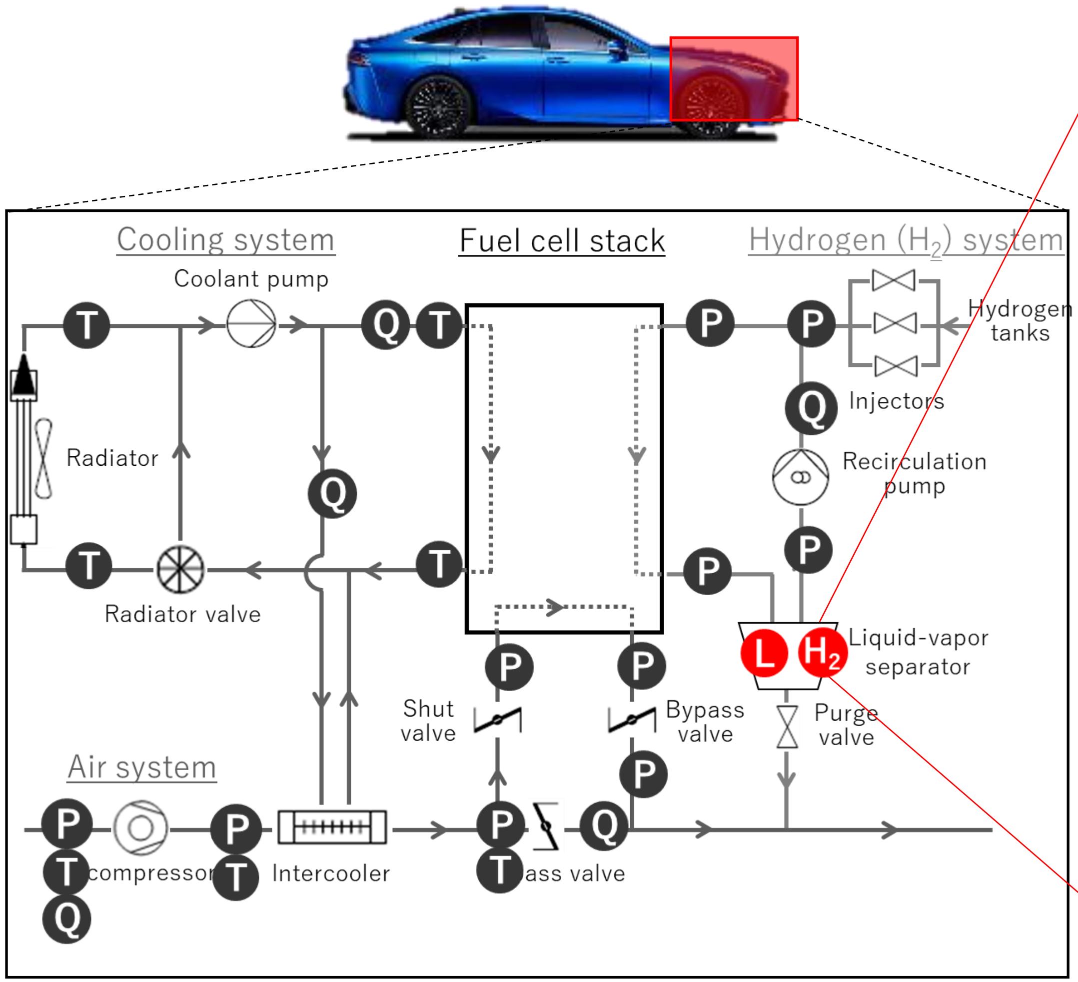
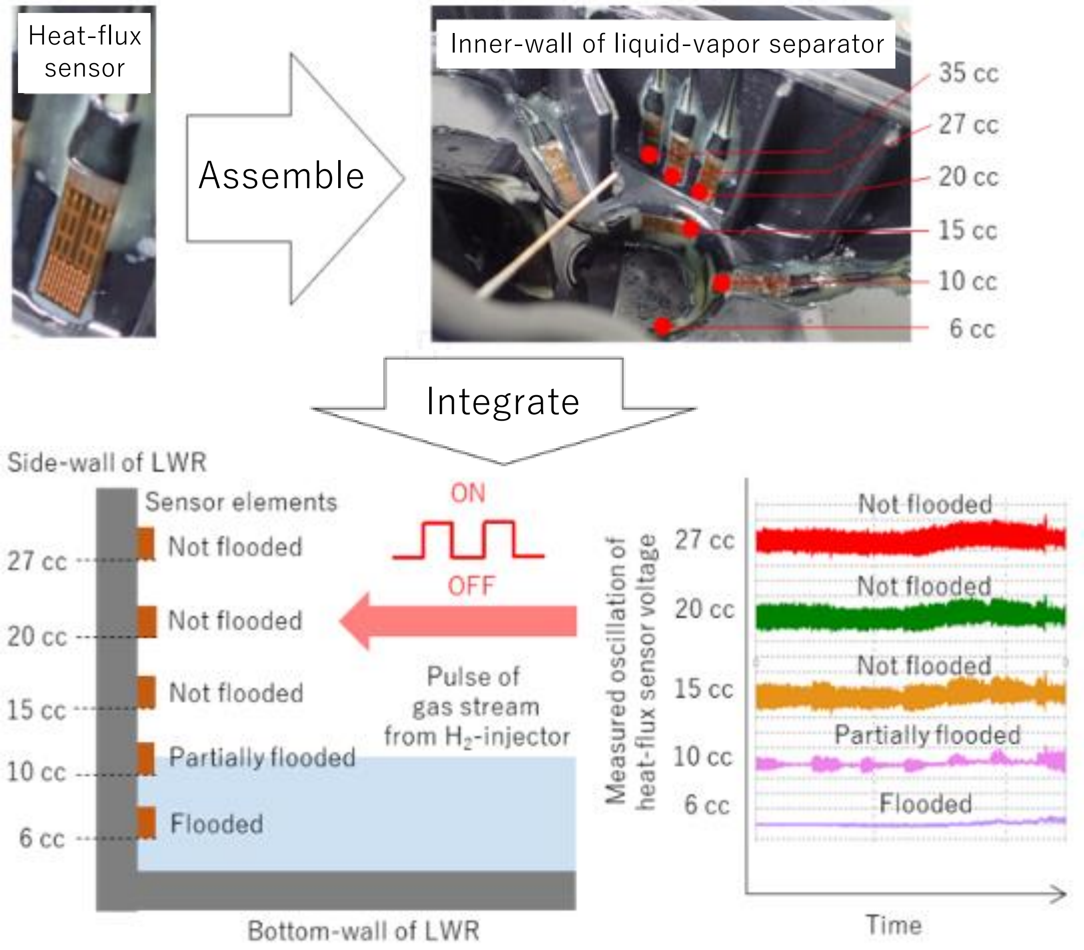


Liquid-level sensor



Model output : Air system dynamics

Air compressor flowrate (cm/act)

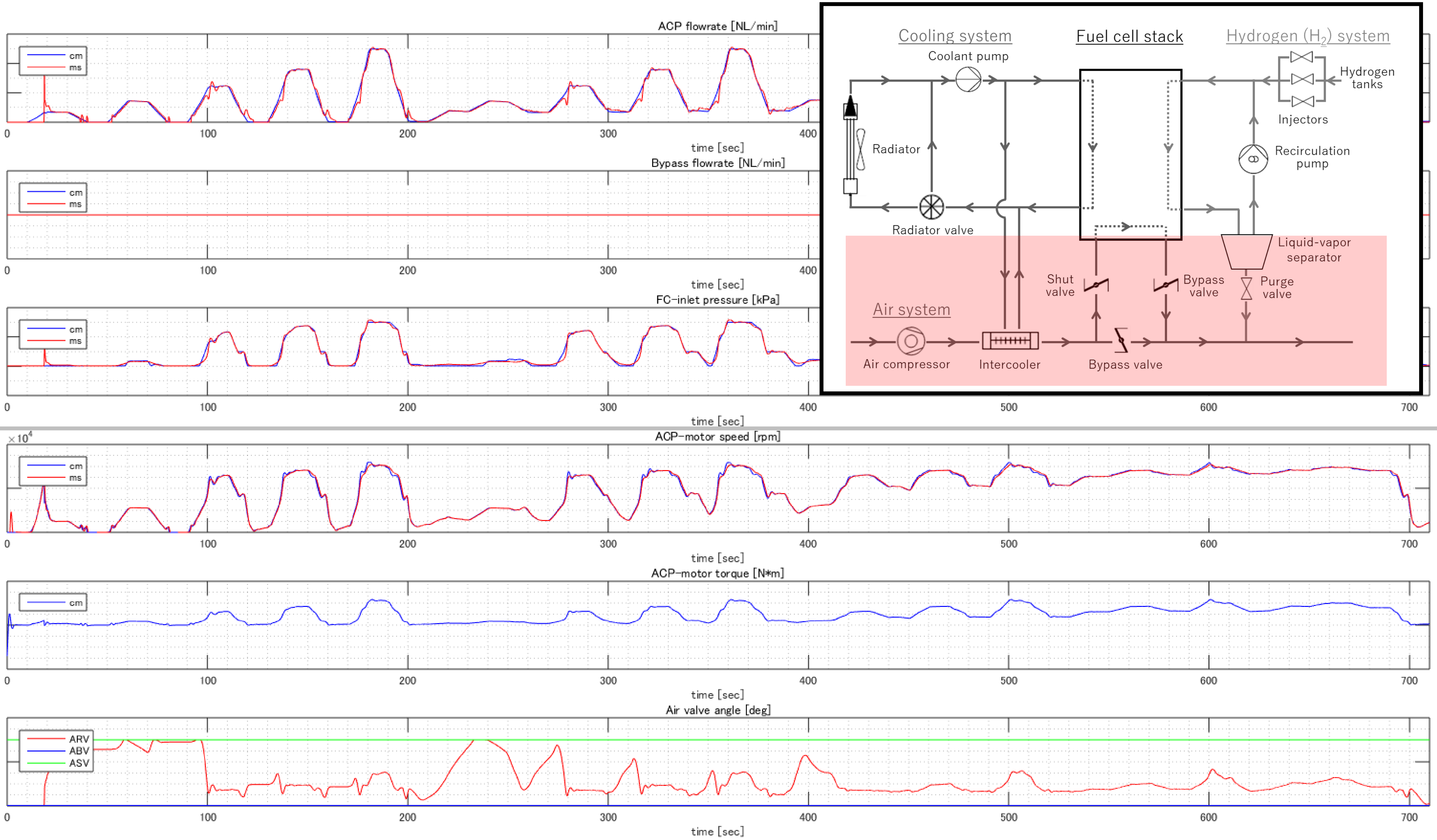
Air flowrate at bypass line (cm/act)

Total pressure at FC-stack inlet (cm/act)

Air compressor rotational speed (cm/act)

Air compressor motor torque (cm/act)

Air valve opening



FC•Platform

Model output : H_2 system dynamics

H2 partial pressure at FC-stack outlet (cm/act)

Total pressure at Injector outlet (cm/act)

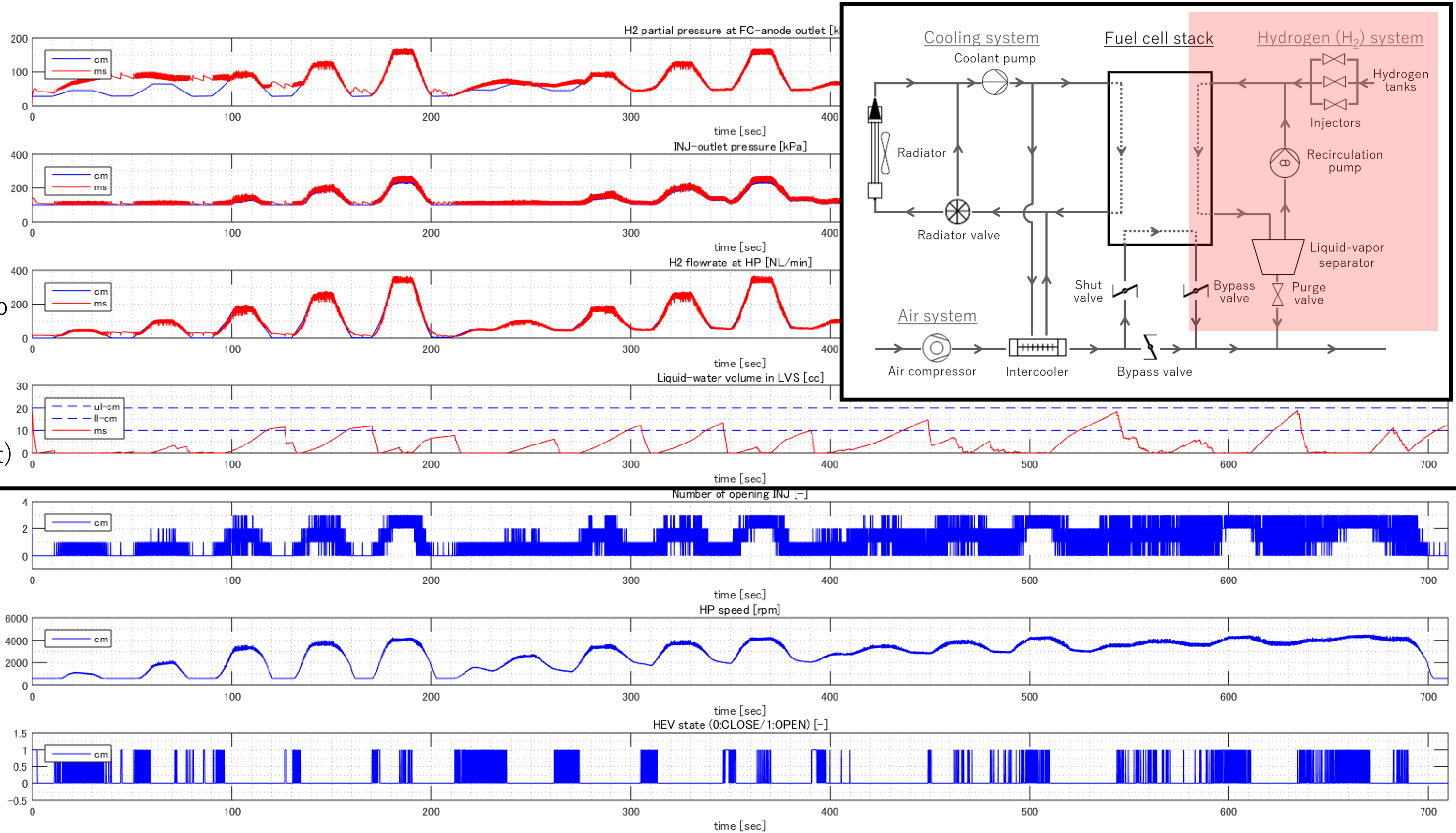
H2 flowrate at recirculation pump (cm/act)

Water level at liquid-vapor separator (cm/act)

Opening injector count

Recirculation pump speed

Purge valve state (open/close)



Model output : Cooling system dynamics

FC-system heat generation / radiation rate

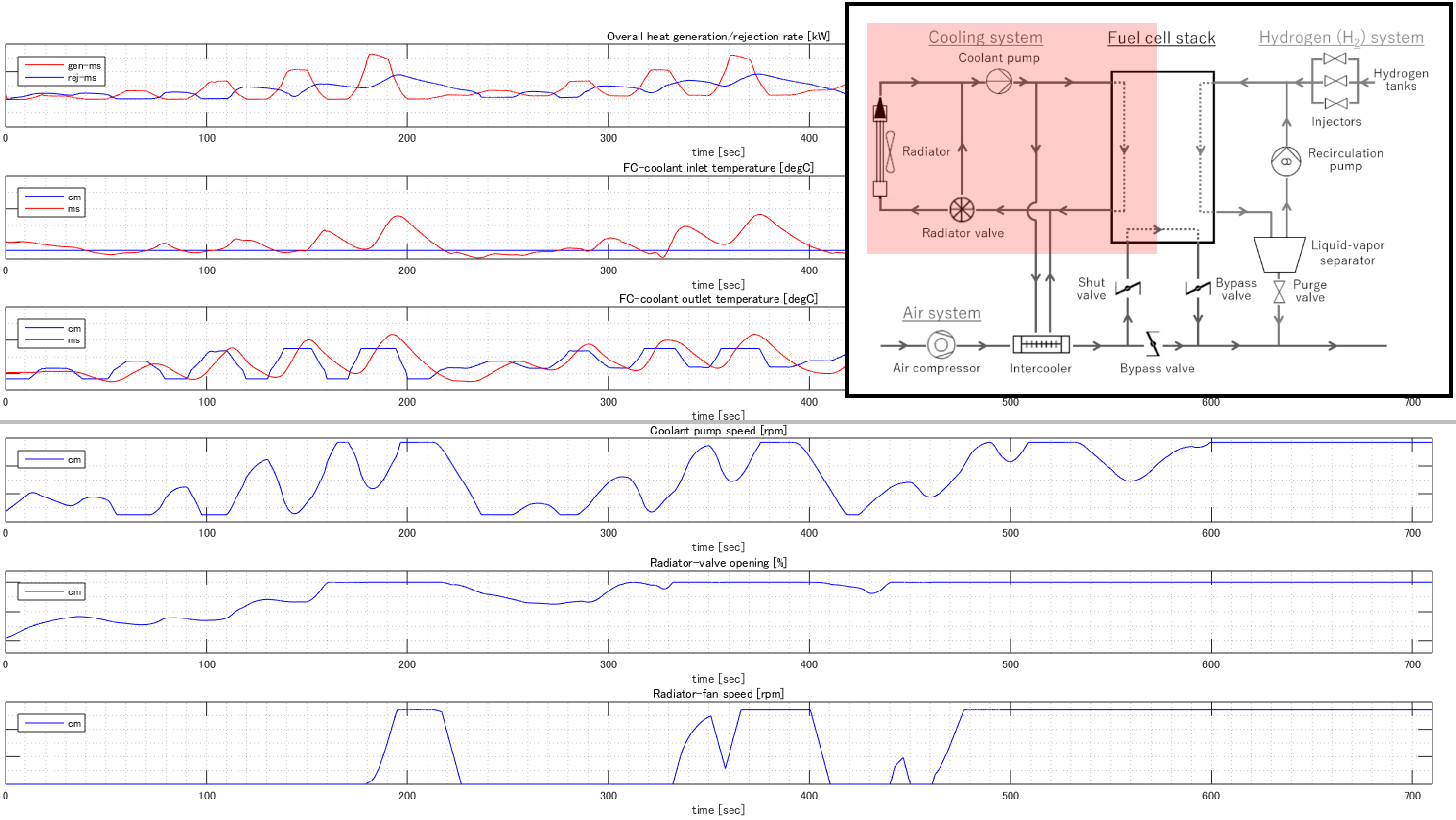
Coolant temperature at FC-stack inlet

Coolant temperature at FC-stack outlet

Coolant pump speed

Radiator valve opening

Radiator fan rotational speed



Model output : Air system controller

Air compressor rotational speed (cm/act)

Air compressor flowrate (cm/act)

Contribution of P-control for command value

Contribution of I-control for command value