MATLAB EXPO

2024.06.11 | 그랜드 인터컨티넨탈 서울 파르나스

Simscape를 이용한 차량 열관리 버추얼 플랜트 개발 및 활용

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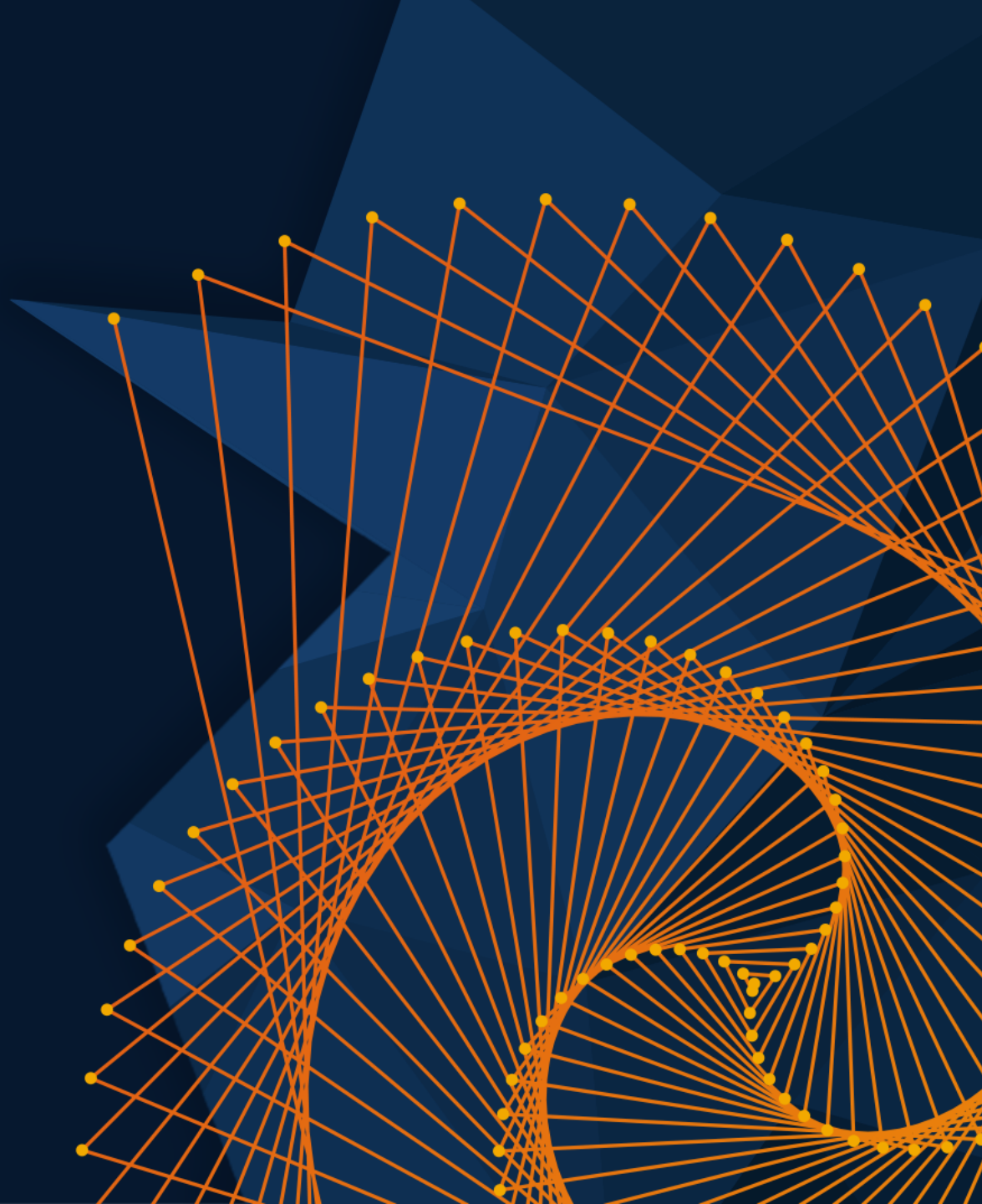
MathWorks

Contents



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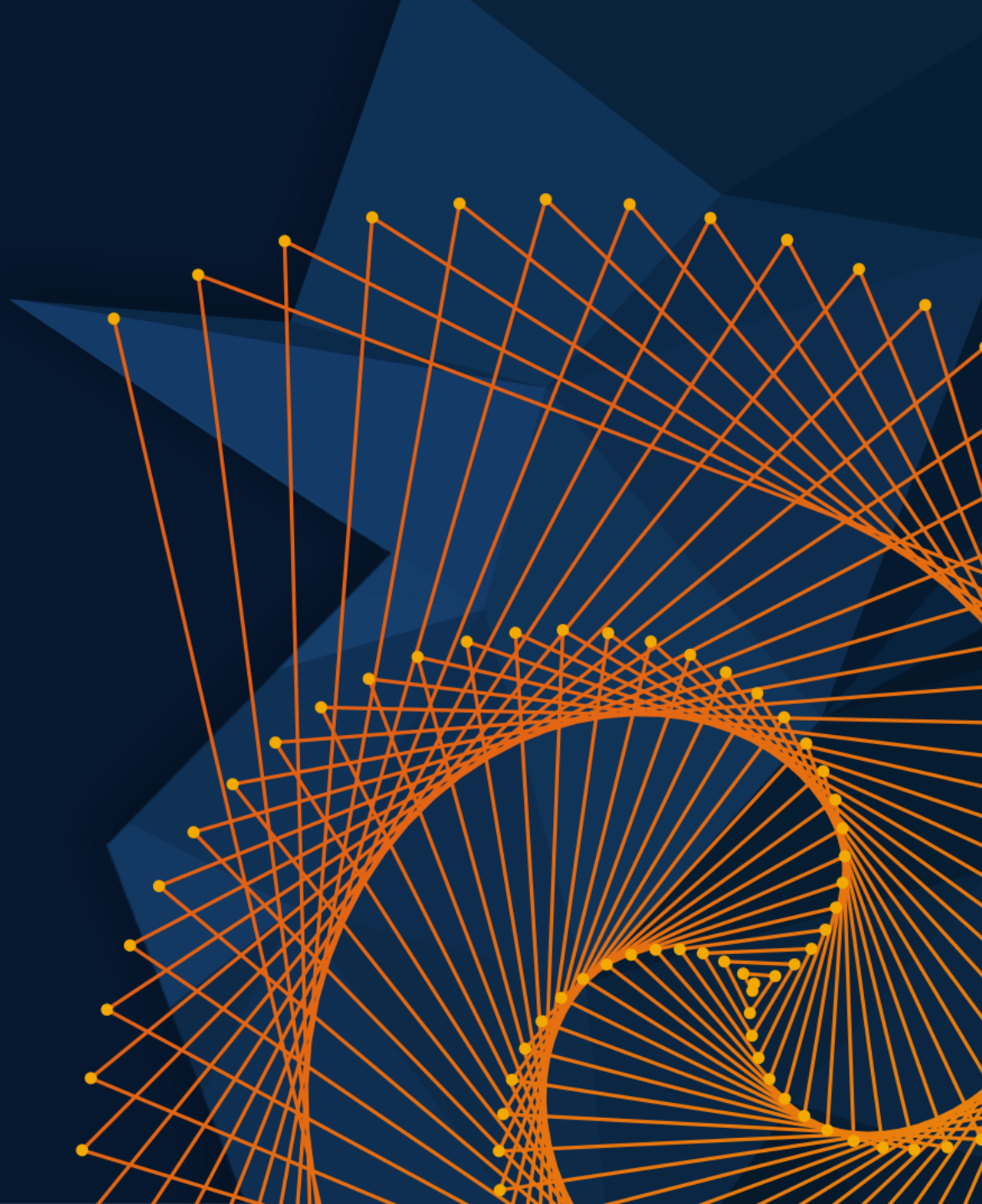
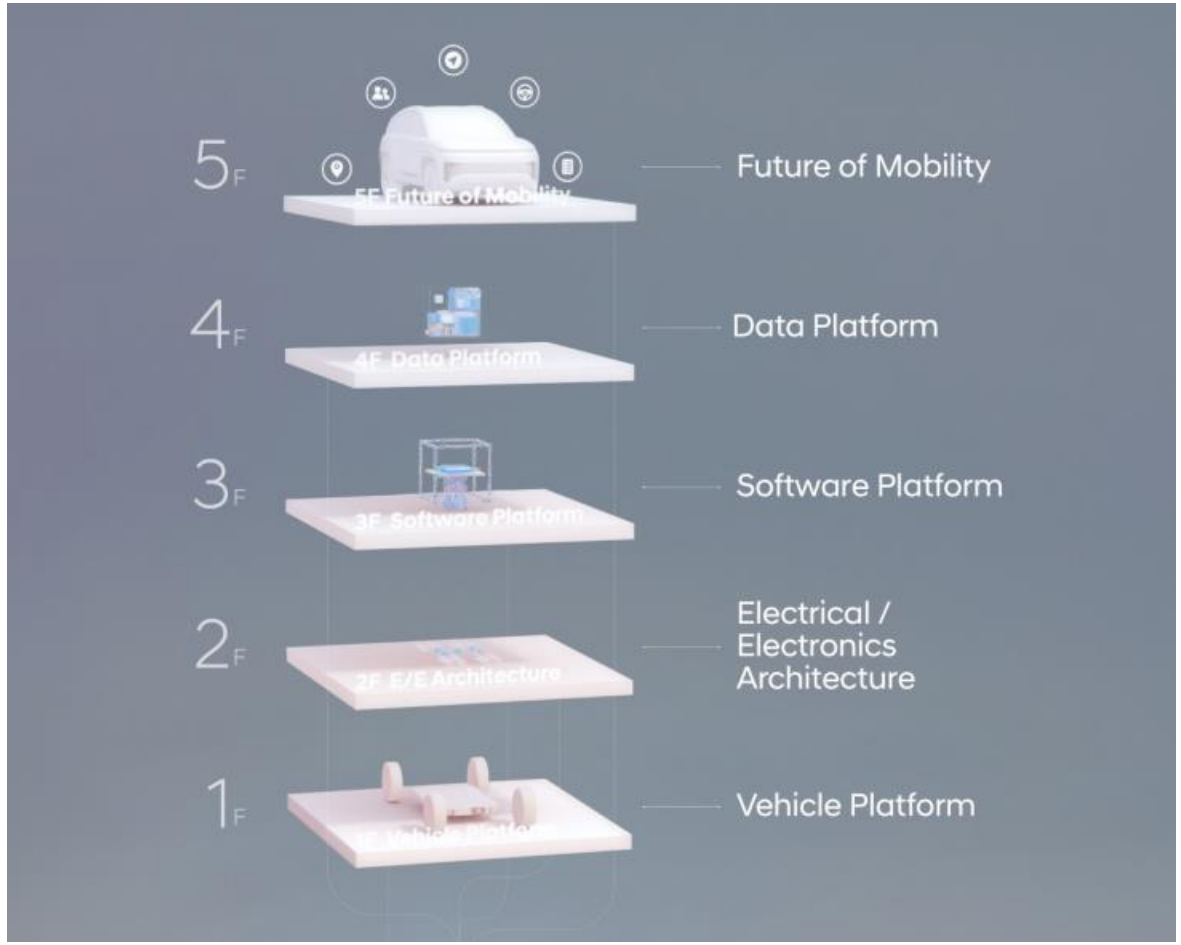


1. Introduction
- SDV

Software-defined Vehicle
refers to a car where software primarily determines the functions and performance of the vehicle.

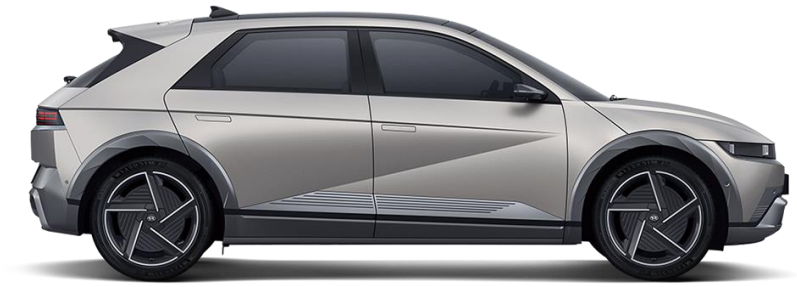


https://www.hyundai.co.kr/live/unlock-the-software-age

1. Introduction

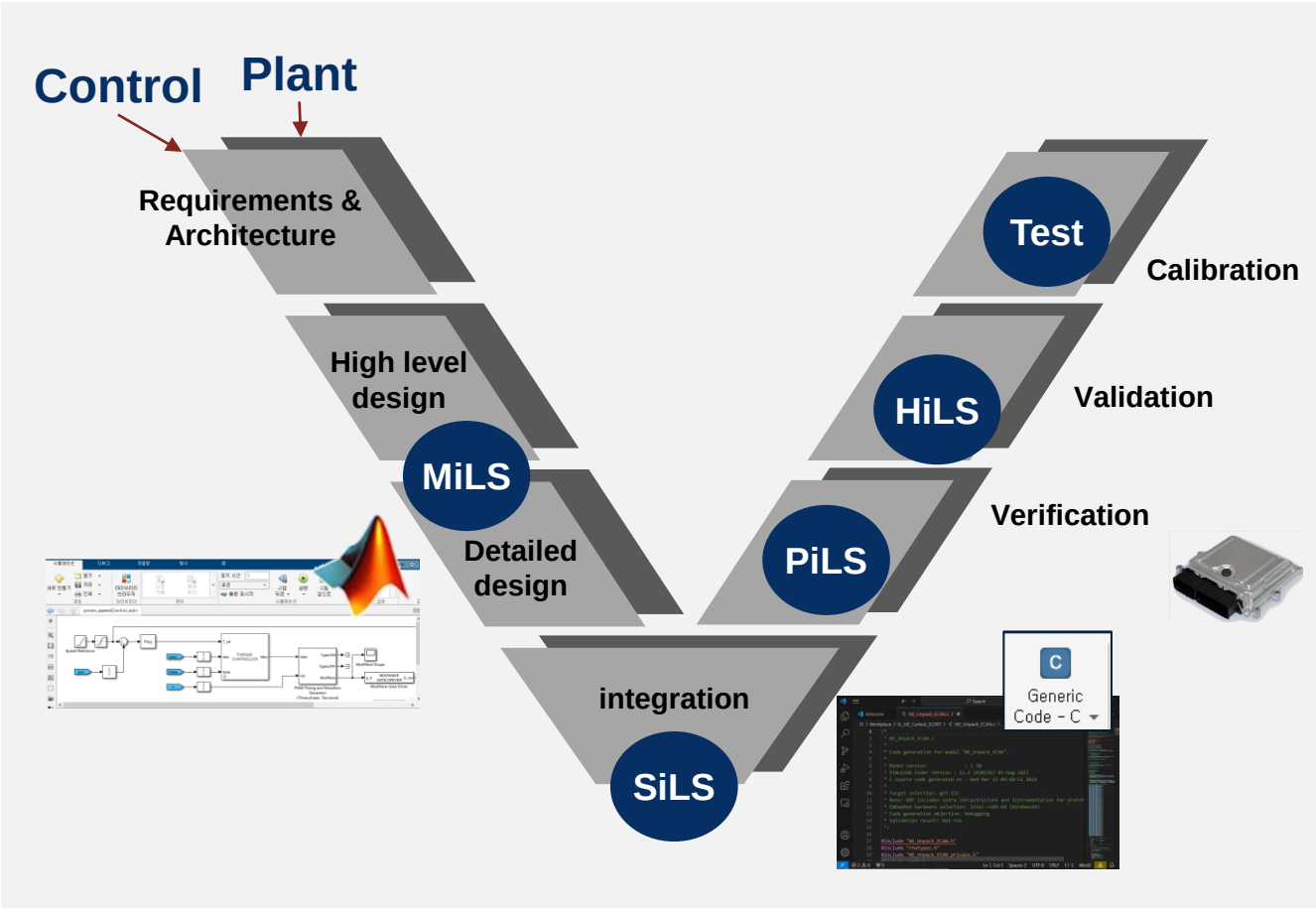
- SDV : Software-defined Vehicle for new value

1. Introduction
- Model-based Development

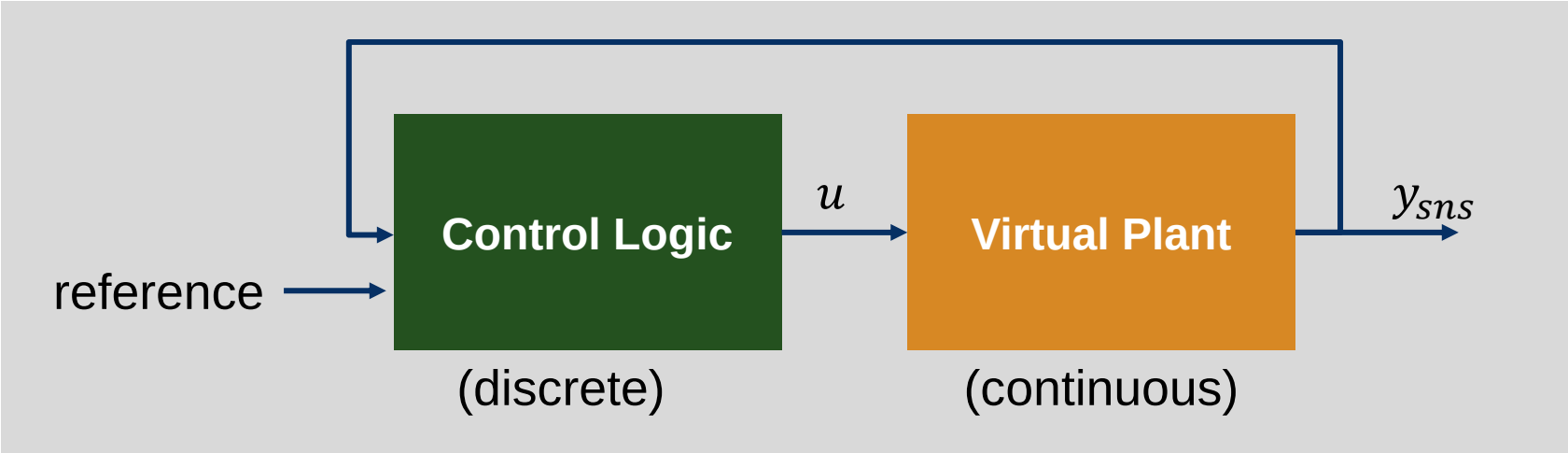


Model-based Development
for better performance and service

→ **Optimization**



1. Introduction
- Control logic & virtual plant



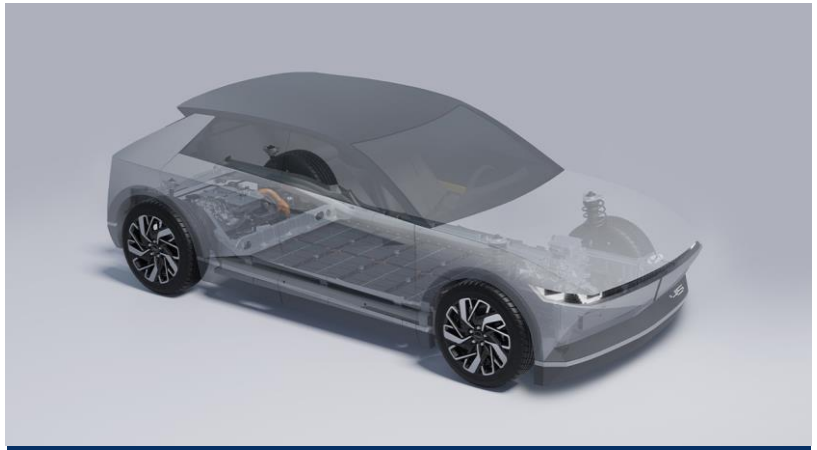
MathWorks

GT Gamma Technologies

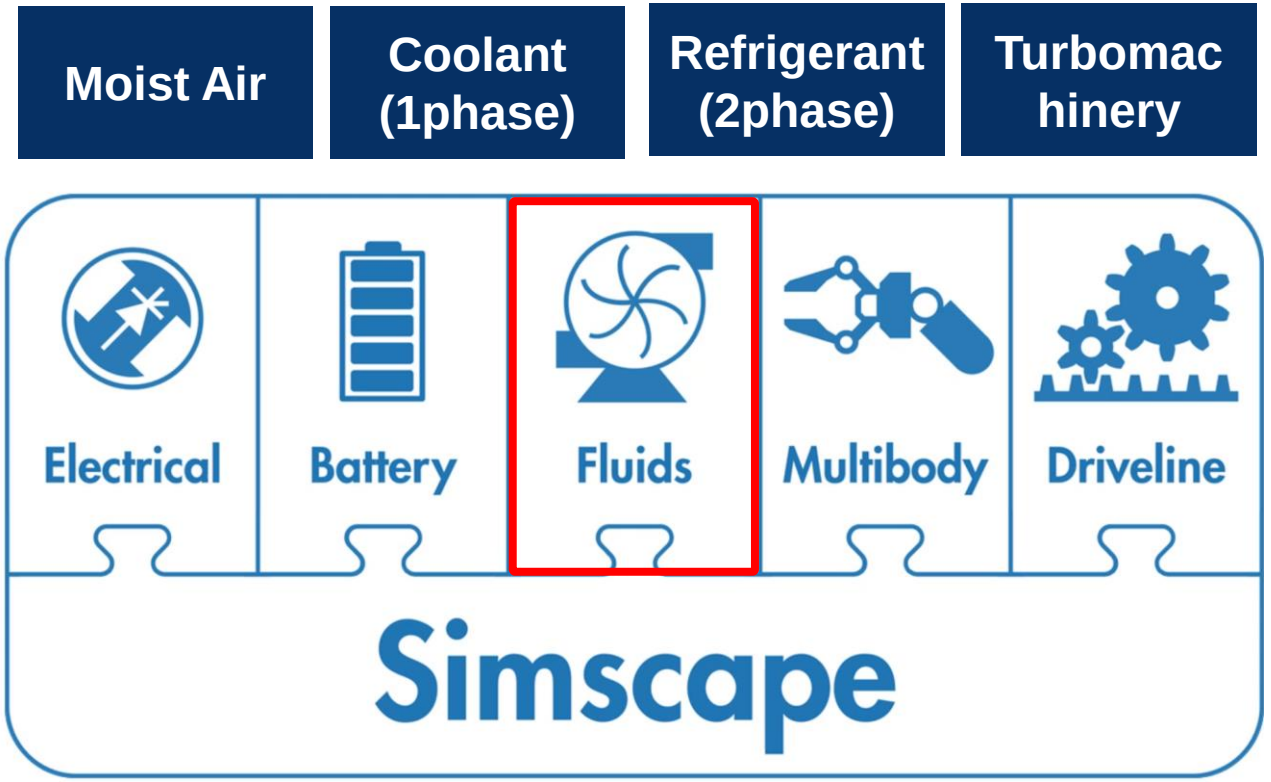
Amesim

MathWorks

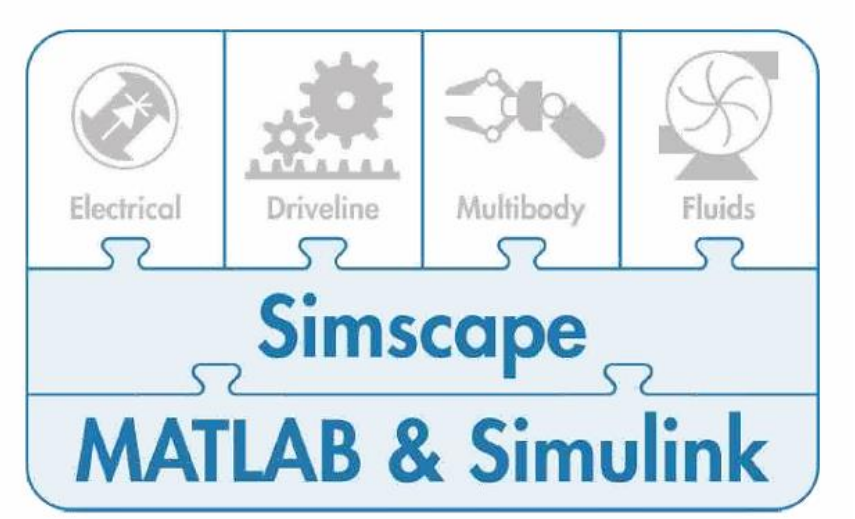
1. Introduction
- Simscape



Simscape
is an equation-based modeling tool for physical systems.



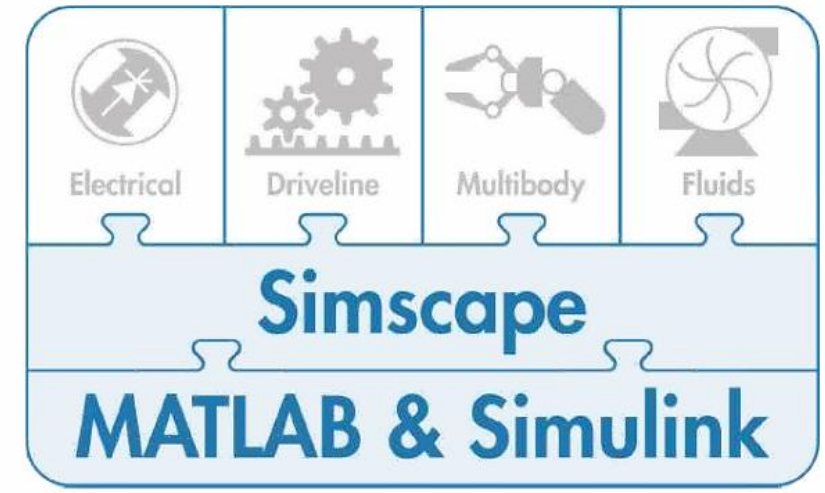
1. Introduction
- topic



Thermal circuit
- Cooling
- Air conditioning

Simulink & Simscape

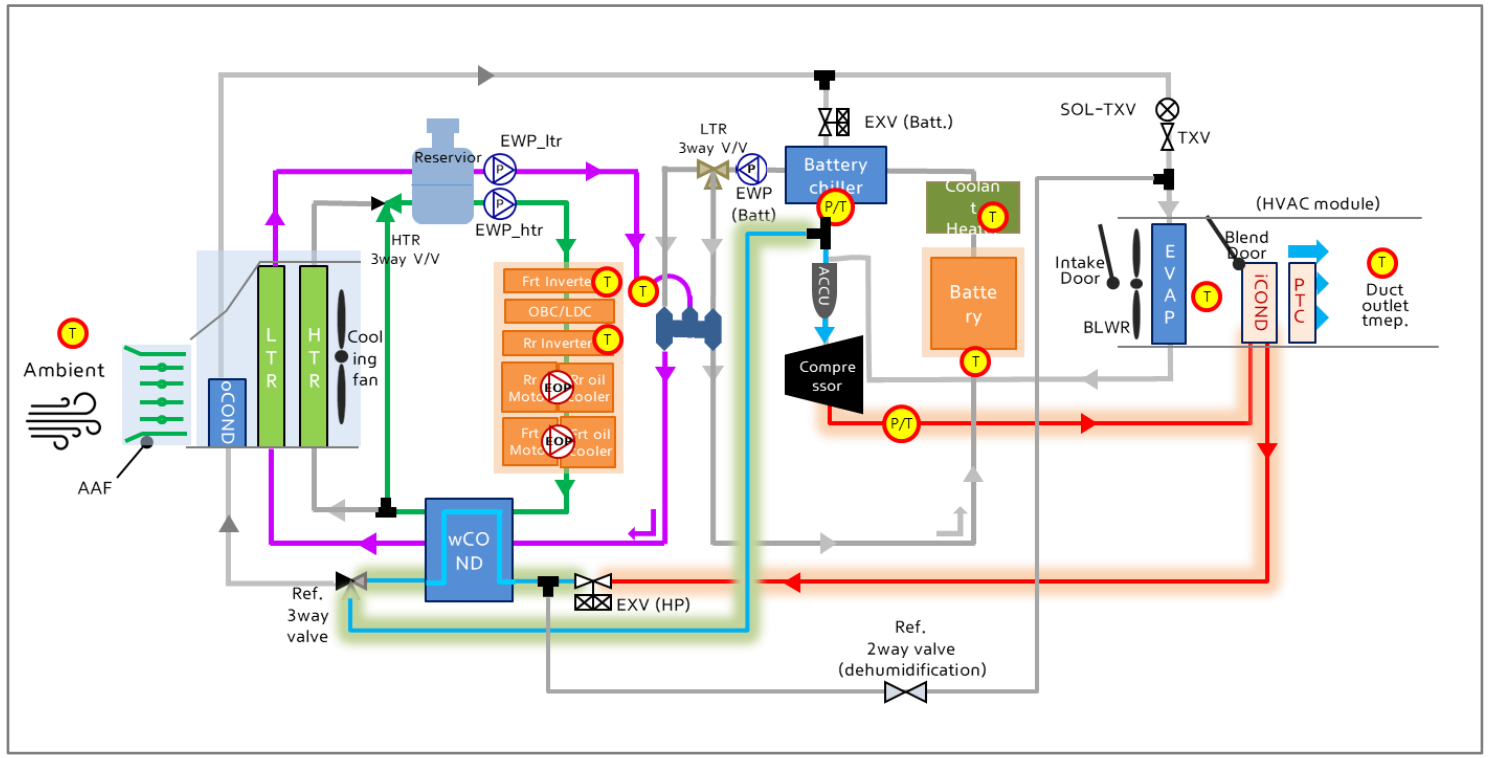
1. Introduction
- topic



Thermal circuit
- Cooling
- Air conditioning

Component
Logic

→ **Integration** → **Verification**



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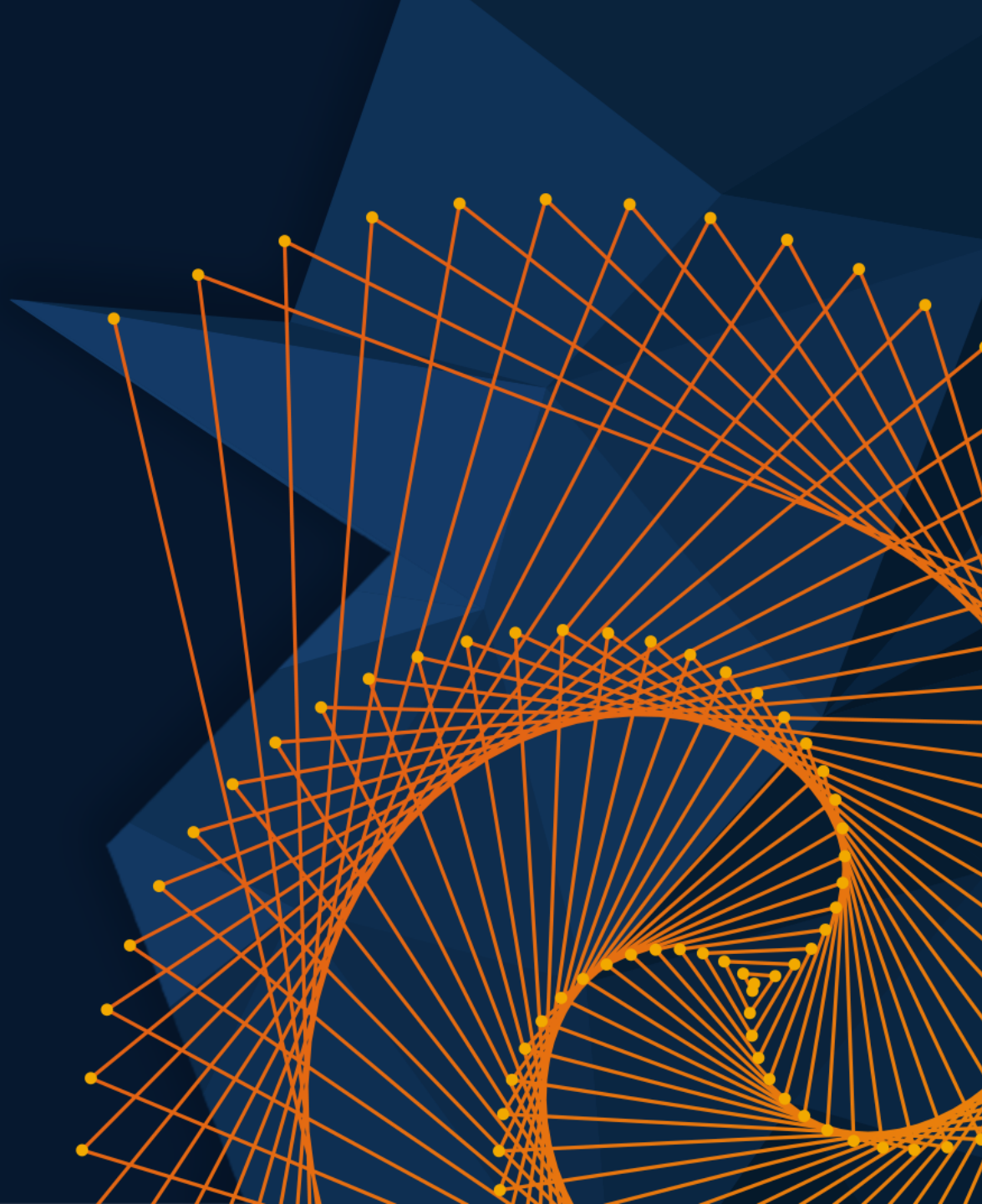
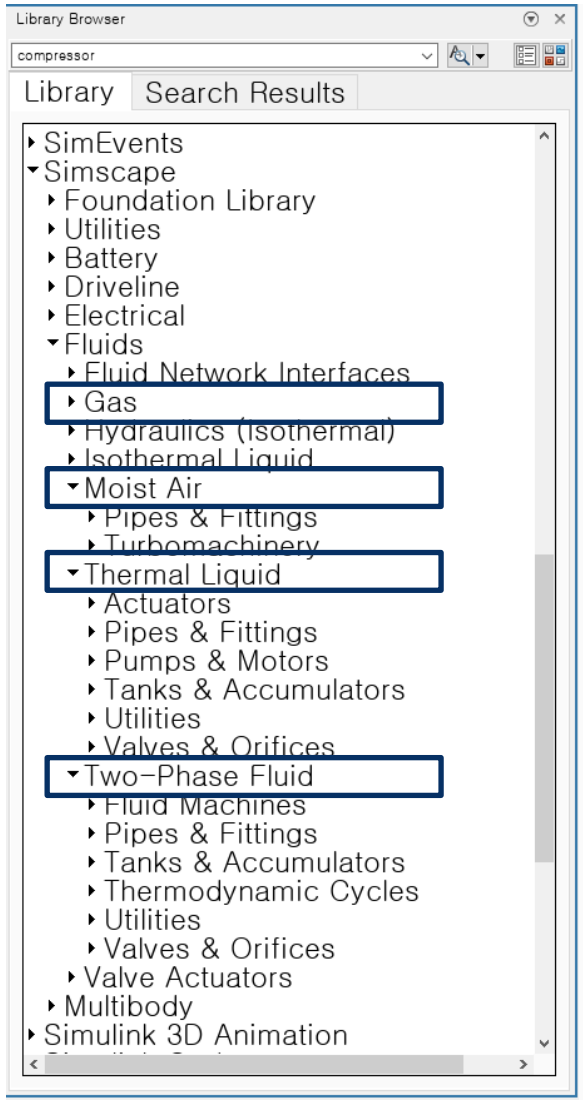
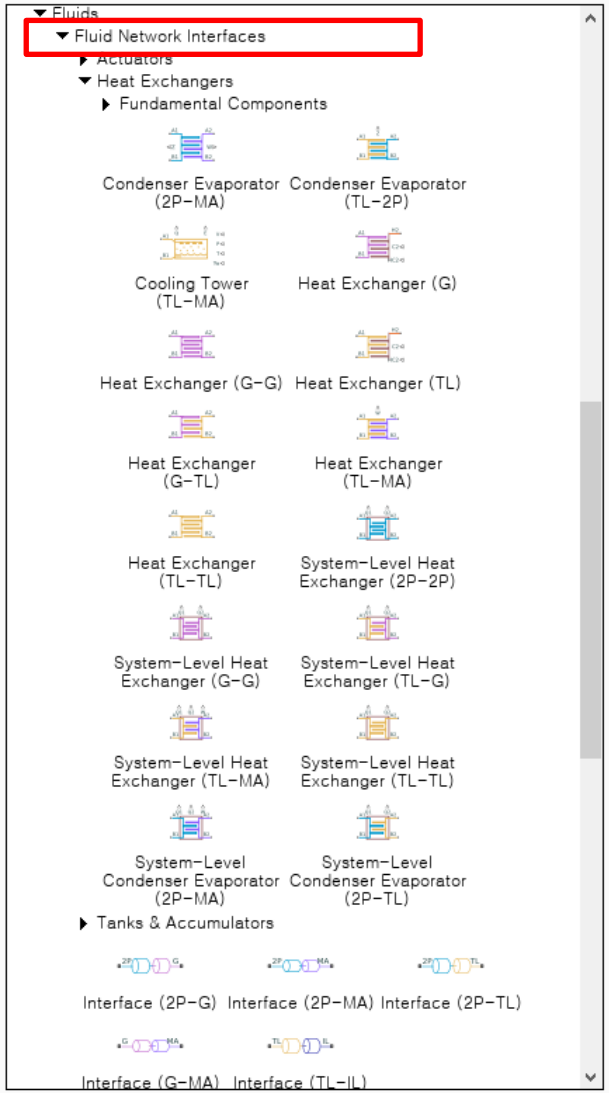


2. Component Level
- Simscape/Fluids library

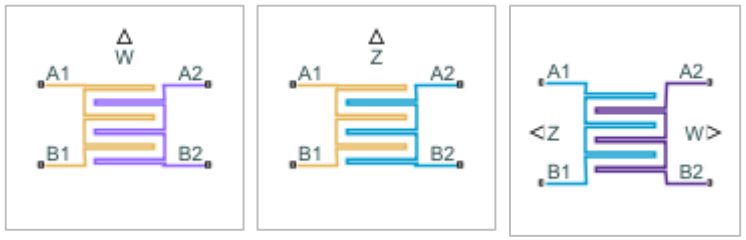




G	Gas
MA	Moist Air
TL	Thermal Liquid
2P	2Phase

2. Component Level
- how to build the HEX

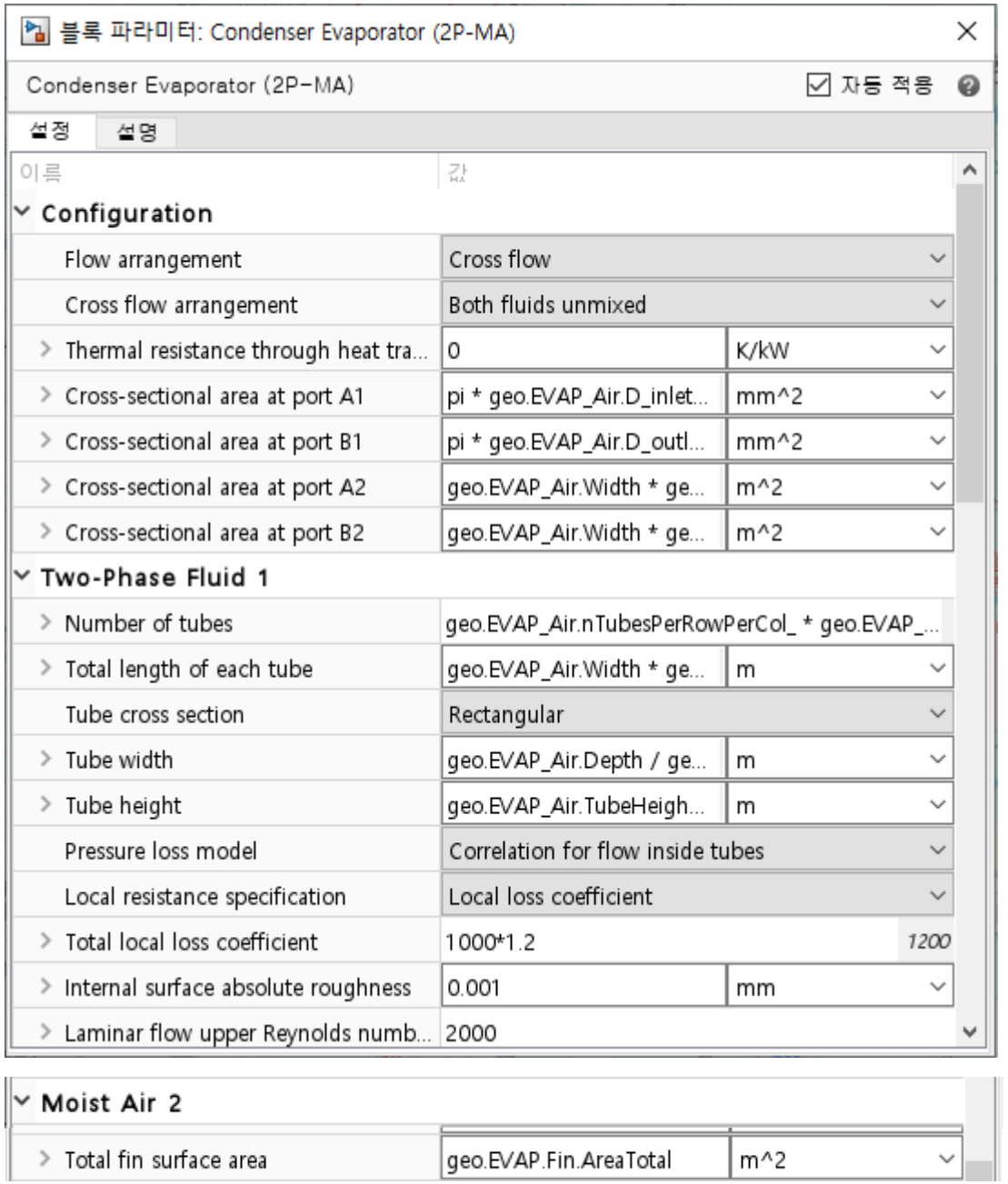
Component



Heat Exchanger : TL-MA, TL-2P, 2P-MA

Geometry info. : Length, Area, …

필요 정보	단위	설명	COND_NE_Pilot
COND.Name	String	모듈이름, 임의값	COND_Air_NE
COND.K	W/m-K	nductivity (alum_300	160
COND.Size.Width	m		0.61
COND.Size.Height	m		0.1266
COND.Size.Depth	m		0.016
COND.TubesInAirFlowDirection	ea	공기방향 열수	1
COND.PassNum	ea	냉매방향 열수	2
COND.TubesPerPass	ea	냉매패스 튜브수들	[8 7]
COND.Tube.nChannel_	ea	튜브당 채널수	18
COND.Tube.Tickness	m		2.50E-04
COND.Tube.Height	m		1.40E-03
COND.Fin.FPDM	ea/dm	Fin Pitch per DeciMeter (산 ~ 골)	80
COND.Fin.Tickness	m		7.00E-05
COND.Fin.height_	m		5.60E-03
COND.Louver.angle_deg	deg		33
COND.Louver.Pitch	m		8.00E-04
COND.Louver.Height	m		5.90E-03



2. Component Level
- how to build the HEX

Component

Pressure loss model	Pressure loss coefficient
Pressure loss coefficient, delta_p/(0....	350
Heat transfer coefficient model	Colburn equation
Coefficients [a, b, c] for a*Re^b*Pr...	[iCond_ref_a1, .8, .33]
Coefficients [a, b, c] for a*Re^b*Pr...	[iCond_ref_a2, .8, .33]
Coefficients [a, b, c] for a*Re^b*Pr...	[iCond_ref_a3, .8, .33]

- Pressure loss coefficients model : $K = \frac{\Delta P}{0.5\rho v^2}$

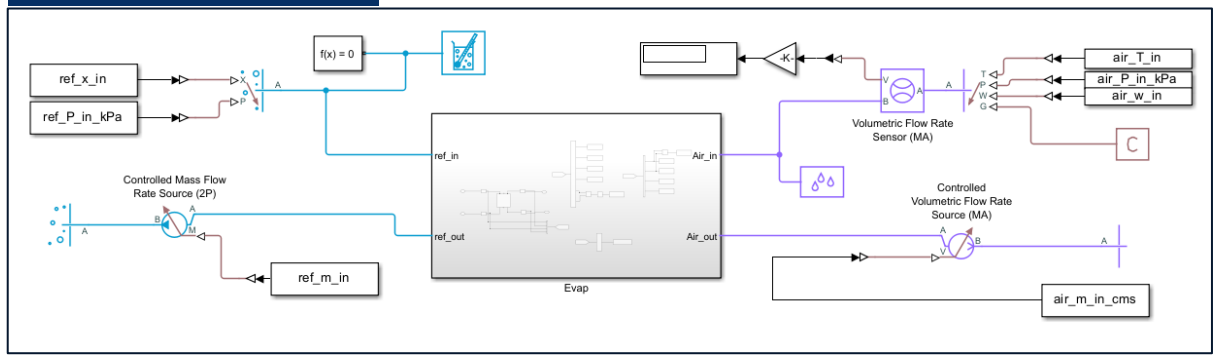
$$h = Nu\frac{k}{D}$$

- Heat transfer coefficients model : Colburn equation
  (the measured data is available and empirical correlations usually fit better)
  - Colburn eq. For liquid and vapor zones : $Nu = aRe^b Pr^c$
  - Cavallini-Zecchin correlation for mixture zone :

$$\mathrm{Nu} = \frac{\mathrm{aRe}_{\mathrm{SL}}^{b}\mathrm{Pr}_{\mathrm{SL}}^{c}\left\{\left[\left(\sqrt{\frac{\rho_{\mathrm{SL}}}{\rho_{\mathrm{SV}}}}-1\right)x_{\mathrm{Out}}+1\right]^{1+b}-\left[\left(\sqrt{\frac{\rho_{\mathrm{SL}}}{\rho_{\mathrm{SV}}}}-1\right)x_{\mathrm{In}}+1\right]^{1+b}\right\}}{(1+b)\left(\sqrt{\frac{\rho_{\mathrm{SL}}}{\rho_{\mathrm{SV}}}}-1\right)(x_{\mathrm{Out}}-x_{\mathrm{In}})}$$

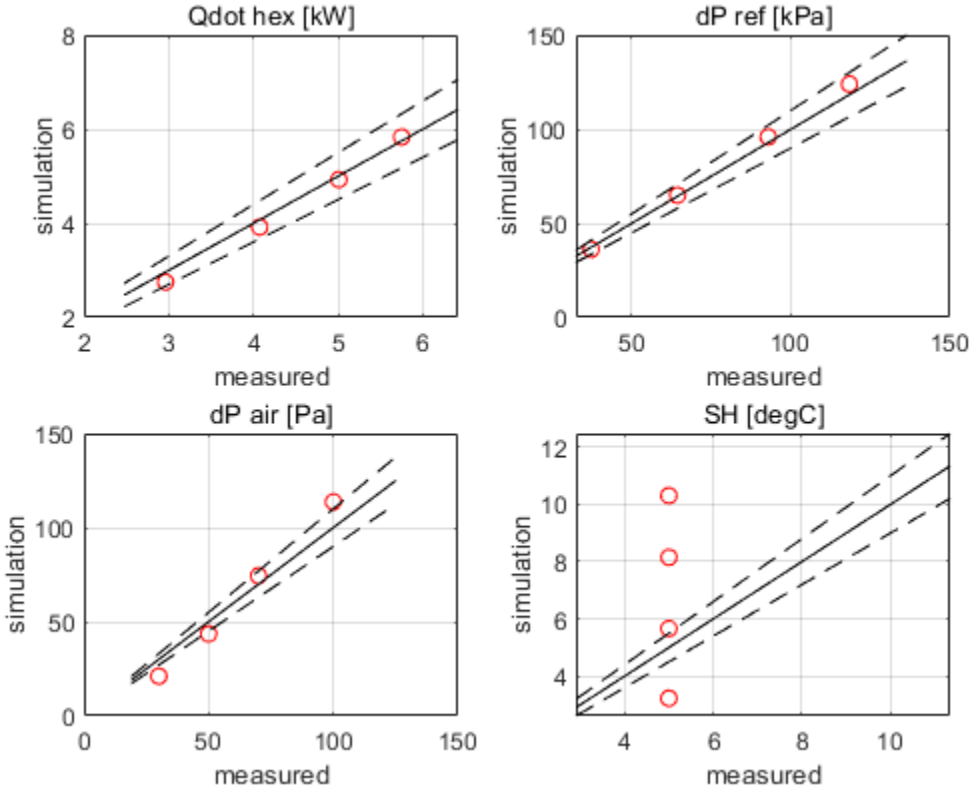
2. Component Level
- how to build the HEX

Unit bench



① Pressure drop
② Heat transfer, Temperature,…

System Identification (Optimization tool)
→ parameter tunning



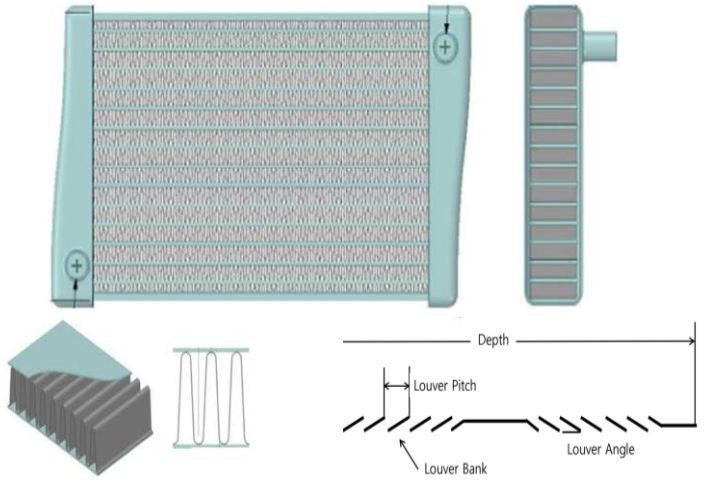
Performance sheet

Time	Air Velocity(m/s)			T_{air_out}(°C)		dP_air(Pa)	Q_air (kW)	Q_refrigerant (kW)	냉매유량 (kg/h)	T_{ref_in}(°C)	T_{ref_out} (°C)	Pref_in(kPa(gauge))	Pref_out (kPa(gauge))	Subcool (°C)
0	2.0	37.0	0.011	54.40	0.011	41.7	3.3	3.3	77	85.5	54.90	1560.6	1541.0	5.0
200	3.0	37.0	0.011	52.80	0.011	75.3	4.5	4.5	108	85.5	54.90	1560.6	1526.4	5.0
400	4.0	37.0	0.011	51.60	0.011	115.8	5.4	5.4	128	85.5	54.90	1560.6	1508.0	5.0
600	5.0	37.0	0.011	49.90	0.011	163.7	6.0	6.0	139	85.5	54.90	1560.6	1494.0	5.0

2. Component Level
- Heat Exchanger (TL-MA)

Geometry

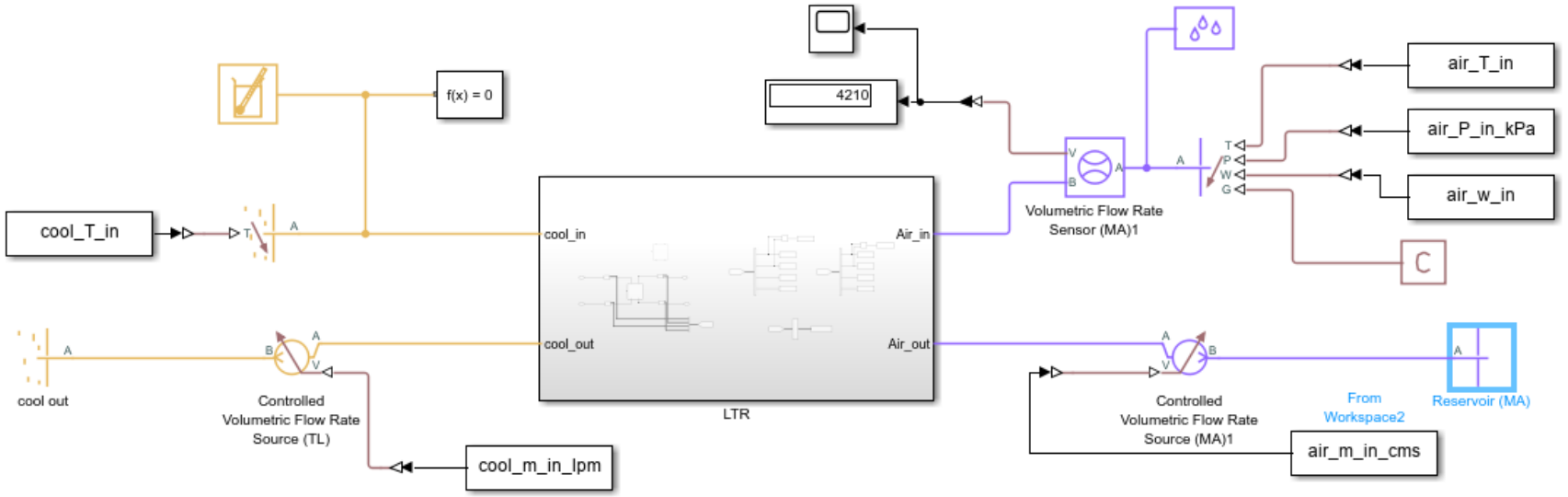
performance



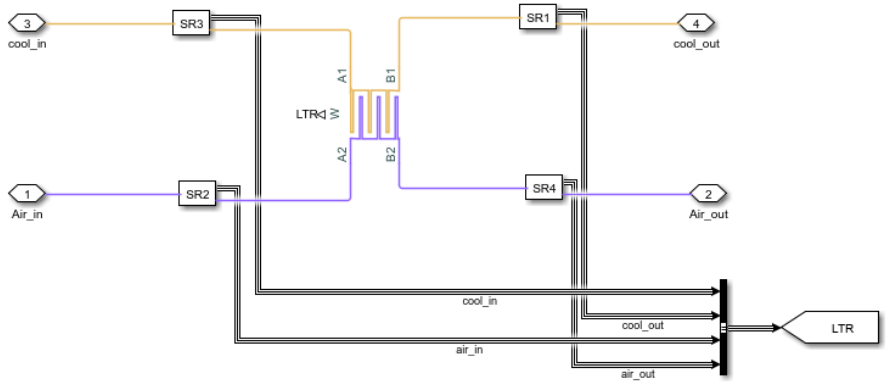
	Input				Output		
Time	Vair [m/s]	Tair_in[degC]	Tcool_in[degC]	pm_coo[lpm]	Qdot_hex[W]	dP_air[Pa]	dP_coo[Pa]
Time	vair_mps	Tair_in	Tcool_in	LPM	Q_W	dP_air_Pa	dP_coo_Pa
0	2	20	40	6	4,665	26,195	16,942.9
50	4	20	40	8	5,805	92,529	17,335.6
100	6	20	40	8	6,309	190,402	17,833.4
150	8	20	40	8	6,556	358,955	18,148.7
200	2	20	40	10	6,064	35,996	30,816.0
250	4	20	40	10	6,464	82,428	21,005.1
300	6	20	40	10	7,079	168,503	22,497.2
350	8	20	40	10	7,393	257,769	22,828.4
400	2	20	40	12	6,917	35,377	25,019.8
450	4	20	40	12	6,952	82,327	26,067.4
500	6	20	40	12	7,826	168,604	27,412.7
550	8	20	40	12	8,080	257,970	27,857.9

Modeling

- Geometry info.
- Pressure loss
- Heat transfer



2. Component Level
- Heat Exchanger (TL-MA)



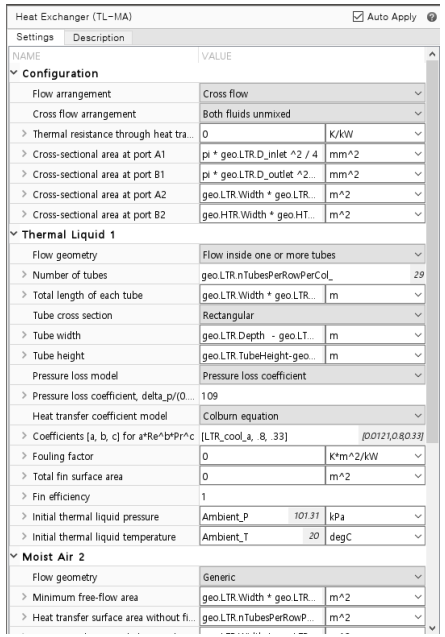
$$dP = K\left(\frac{1}{2}\rho V^2\right)$$

(pressure loss coefficient)

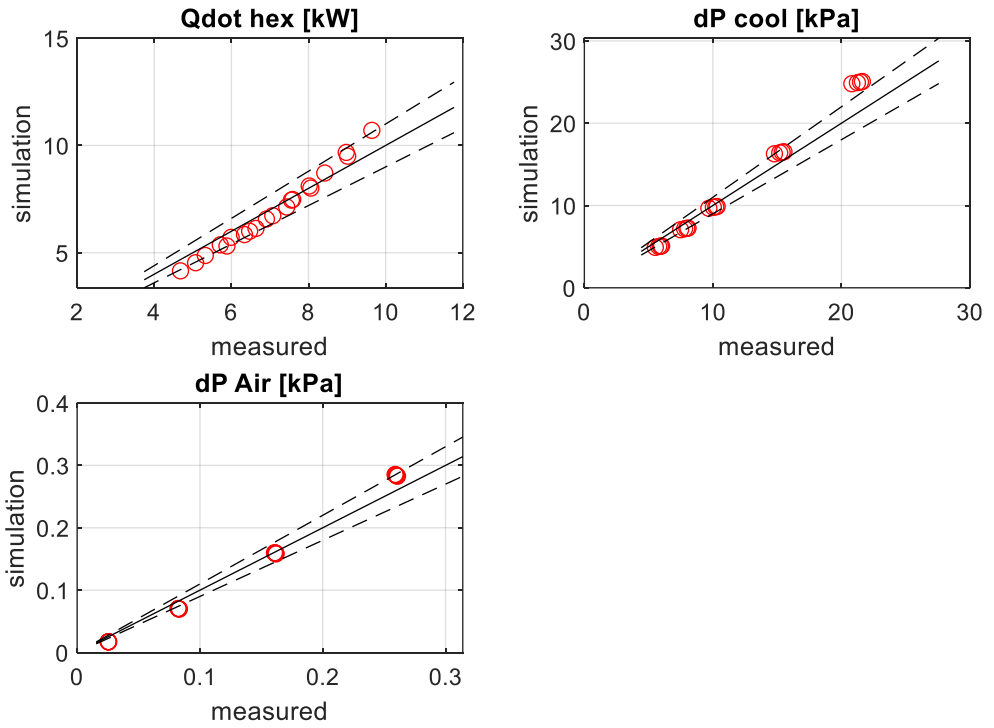
$$h = Nu\frac{k}{D}$$

$$Nu = aRe^b Pr^c$$

(Colburn equation)



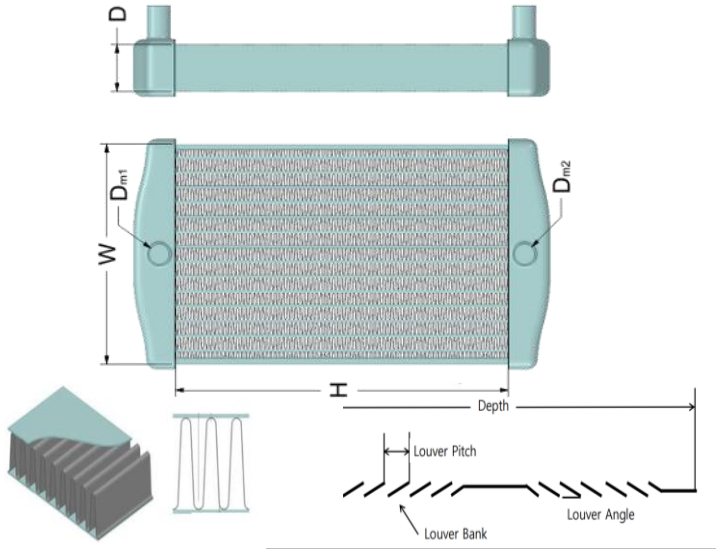
Pressure drop → **Heat transfer**



2. Component Level
- Heat Exchanger (2P-MA)

Geometry

performance



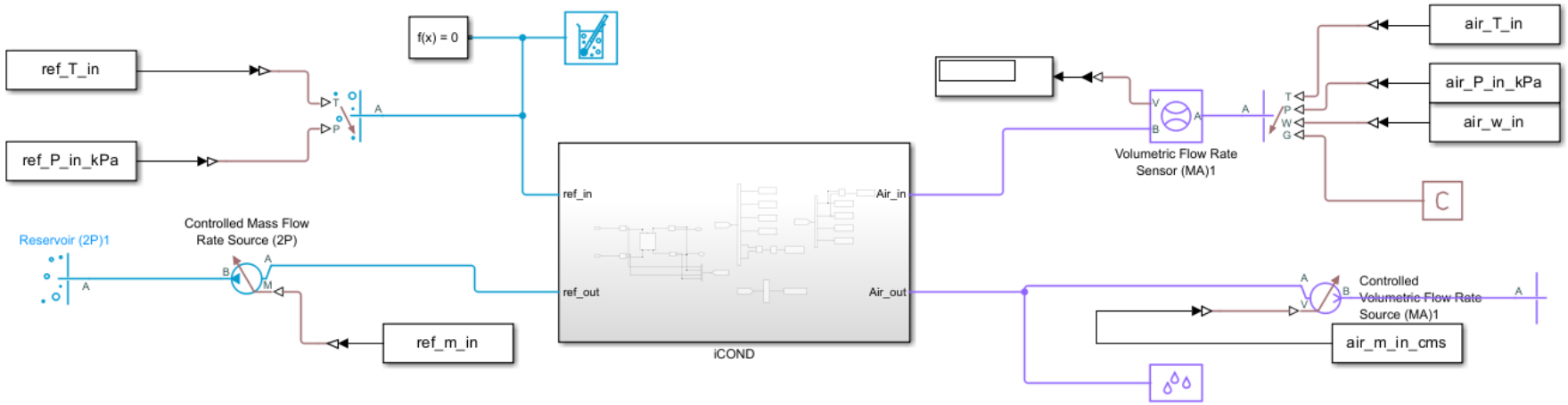
Air side

Refrigerant side

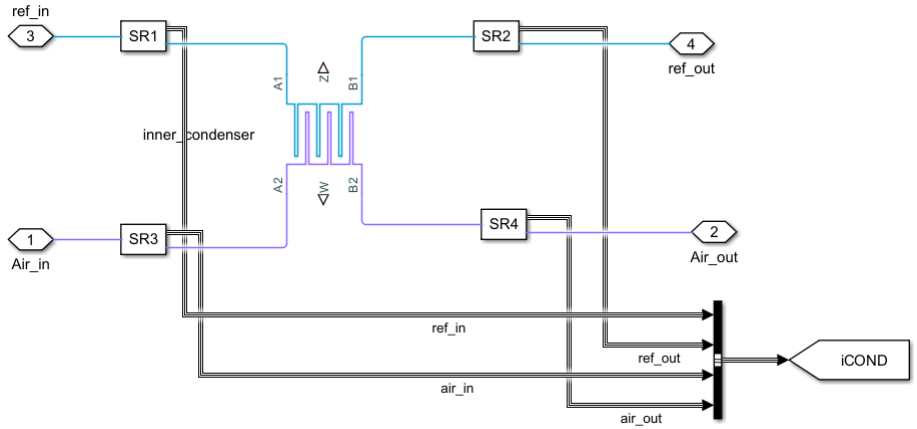
Time	Air side							Refrigerant side						
	Air flow (CMS)	Tair_in (C)	Hd_in abs(kg/kg)	Tair_out (C)	Hd_out abs(kg/kg)	dP_air(Pa)	Q_air (kW)	Q_refriger ant (kW)	m_ref (kg/s)	Tref_in (C)	Tref_out (C)	Pref_in(kPa(gauge))	Pref_out (kPa(gauge))	Subcool (C)
Time	CMS	Tair_in	Hd_in_abs	Tair_out	Hd_out_abs	dP_air_Pa	Q_air_kW	Q_refriger	m_ref_kgPs	Tref_in	Tref_out	Pref_in_kPa_gauge	Pref_out_kPa_gauge	SC
0	0.0000	15	0.004	59.9	0.004	112.4	6.05	6.05	0.0355	100	64.78	2,257.00	2,251.13	11.00
100	0.0000	15	0.004	61.1	0.004	101.2	5.44	5.44	0.0319	100	64.8	2,257.00	2,252.03	11.00
200	0.0000	15	0.004	62.3	0.004	88.9	4.79	4.79	0.0281	100	64.82	2,257.00	2,252.93	11.00
300	0.0000	15	0.004	63.5	0.004	62.2	4.09	4.09	0.024	100	64.83	2,257.00	2,253.73	11.00
400	0.0000	15	0.004	64.6	0.004	45.2	3.34	3.34	0.0196	100	64.84	2,257.00	2,254.53	11.00
500	0.07	15.09	0.004	67.06	0.004	48.06	3.73	3.57	0.02816323	102.00	67.46	2,263.54	2,255.65	5.28
600	0.10	15.00	0.004	67.14	0.004	76.60	5.11	5.21	0.03687138	102.03	67.49	2,266.56	2,256.48	9.35
700	0.13	14.96	0.004	68.11	0.004	111.21	6.32	6.32	0.04470938	102.06	67.26	2,262.08	2,249.70	9.35
800	0.07	-6.02	0.004	29.67	0.004	48.55	2.54	2.76	0.01799356	44.41	29.12	899.71	895.40	9.95
900	0.10	-6.03	0.004	28.83	0.004	79.33	3.45	3.67	0.02353423	44.35	29.16	900.24	894.47	9.91
1000	0.13	-6.12	0.004	27.85	0.004	114.55	4.30	4.45	0.02926858	44.40	29.15	900.38	892.98	9.86
1100	0.07	-7.12	0.004	21.48	0.004	48.06	2.51	2.75	0.01717866	35.96	20.91	704.07	703.79	10.03

Modeling

- Geometry info.
- Pressure loss
- Heat transfer



2. Component Level
- Heat Exchanger (TL-MA)



$$dP = K\left(\frac{1}{2}\rho V^2\right)$$

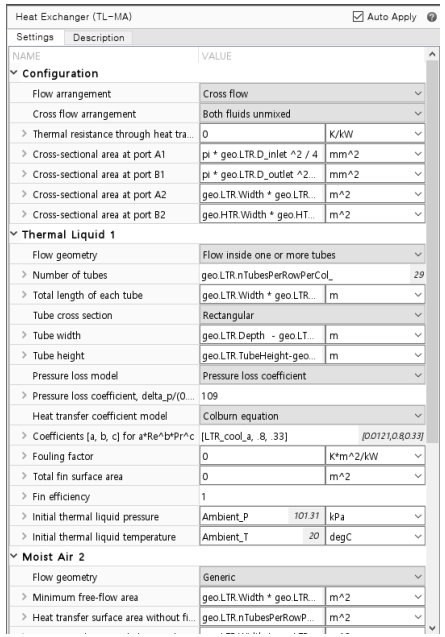
(pressure loss coefficient)

$$h = Nu\frac{k}{D}$$

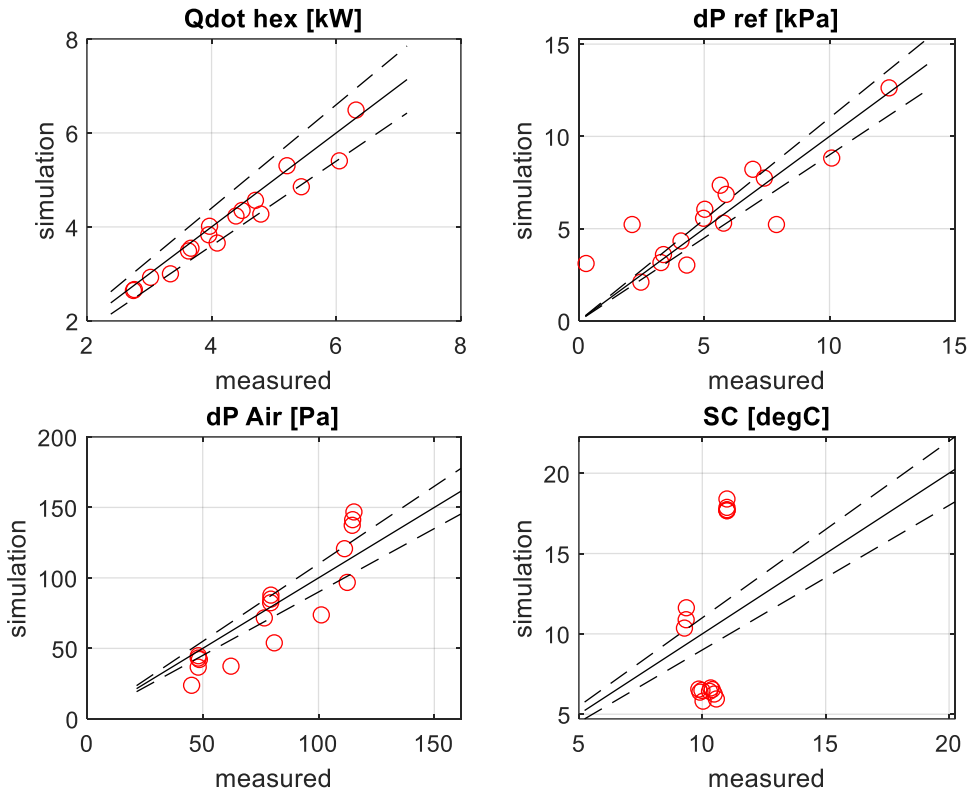
$$Nu = aRe^b Pr^c$$

(Colburn equation)

※ each phase



Pressure drop → **Heat transfer**



2. Component Level
- Compressor(2P)

Geometry

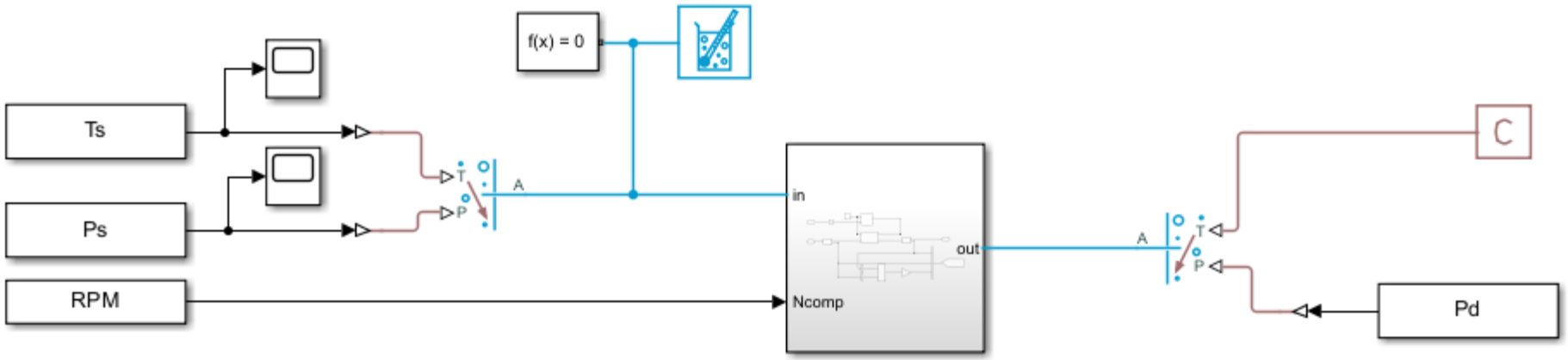
performance

rpm PR η_k

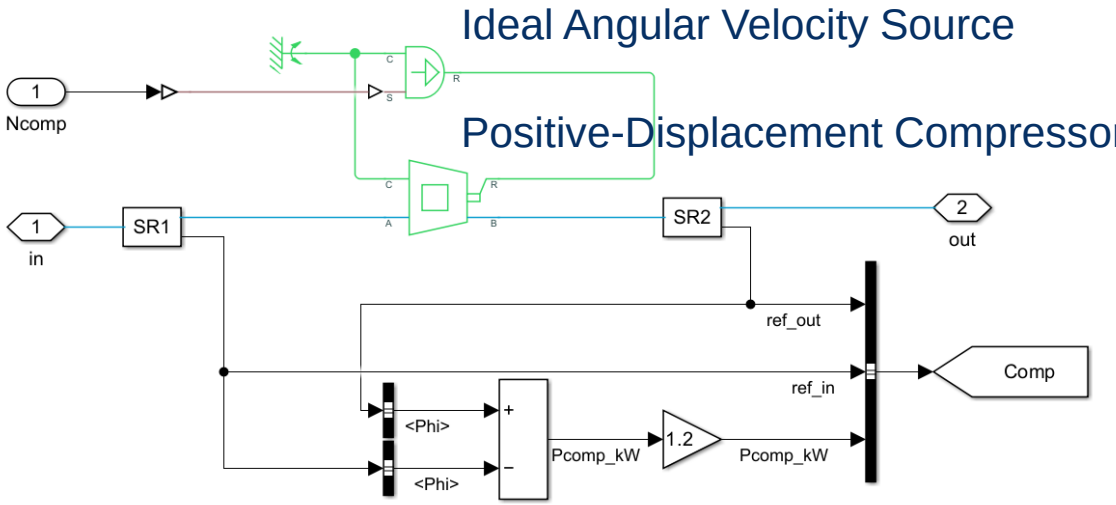
Time	RPM	PR	Ps	Ts	Pd	Td	Power	Torque	Torque	Flow rate			
	(rpm)	(Discharge/Suction Pressure Ratio)	(bar, abs) Ps	(degC) Ts	(bar, abs) Pd	(degC) Td	(HP) Power	(kW) Power	(kg-m) Torque	(N-m) Torque	(kg/h) Flow rate	(kg/min) Flow rate	Adiabatic (Mechanical Eff.) (%)	Adiabatic (Volumetric Eff.) (%)	Adiabatic (Isentropic Eff.) (%)
1	1500	3.33	3.00	2.04	10.00	10.00	9.12	0.00	0.31	0.00	0.00	59.08	0.00	93.3	94.2	58.3
5	3000	3.33	3.00	2.04	10.00	10.00	9.12	57.15	0.00	1.32	0.00	0.00	120.98	0.00	90.9	93.4	64.3
10	5000	3.33	3.00	2.04	10.00	10.00	9.12	57.91	0.00	2.36	0.00	0.00	202.65	0.00	88.6	94.0	62.3
15	1500	5.00	3.00	2.04	10.60	15.00	14.28	96.82	0.00	1.02	0.00	0.00	51.13	0.00	84.7	79.0	46.8
20	3000	5.00	3.00	2.04	10.60	15.00	14.28	75.84	0.00	1.75	0.00	0.00	114.04	0.00	86.6	88.1	62.9
25	5000	5.00	3.00	2.04	10.60	15.00	14.28	74.31	0.00	2.94	0.00	0.00	194.19	0.00	86.1	90.1	64.2
30	7000	5.00	3.00	2.04	10.60	15.00	14.28	76.99	0.00	4.23	0.00	0.00	287.75	0.00	85.8	86.6	64.1
35	9000	5.00	3.00	2.04	10.60	15.00	14.28	79.54	0.00	5.46	0.00	0.00	371.84	0.00	86.8	88.7	57.0
40	10000	5.00	3.00	2.04	10.60	15.00	14.28	82.36	0.00	6.58	0.00	0.00	360.70	0.00	84.5	63.8	53.4
45	3000	6.67	3.00	2.04	10.60	20.06	19.29	92.87	0.00	2.18	0.00	0.00	109.21	0.00	86.0	84.3	56.7
50	5000	6.67	3.00	2.04	10.60	20.06	19.29	90.18	0.00	3.46	0.00	0.00	186.96	0.00	84.1	88.1	61.6
55	7000	6.67	3.00	2.04	10.60	20.06	19.29	91.06	0.00	4.98	0.00	0.00	266.56	0.00	85.2	84.9	60.3
60	9000	6.67	3.00	2.04	10.60	20.06	19.29	95.28	0.00	6.29	0.00	0.00	331.50	0.00	83.8	83.9	57.5
65	10000	6.67	3.00	2.04	10.60	20.06	19.29	96.64	0.00	7.58	0.00	0.00	348.54	0.00	82.5	84.0	53.7
70	3000	8.33	3.00	2.04	10.60	25.00	24.47	110.35	0.00	2.57	0.00	0.00	103.01	0.00	83.8	79.5	51.3
75	5000	8.33	3.00	2.04	10.60	25.00	24.47	104.06	0.00	4.06	0.00	0.00	176.60	0.00	81.9	84.8	57.9
80	7000	8.33	3.00	2.04	10.60	25.00	24.47	103.69	0.00	5.81	0.00	0.00	250.32	0.00	82.4	82.9	58.2
85	9000	8.33	3.00	2.04	10.60	25.00	24.47	105.33	0.00	8.99	0.00	0.00	266.56	0.00	81.4	80.5	56.4
90	10000	8.33	3.00	2.04	10.60	25.00	24.47	108.03	0.00	8.42	0.00	0.00	335.72	0.00	81.1	77.7	49.2

Modeling

- Environment
- HEX



2. Component Level
- Compressor(2P)



Mass flowrate & **Power**

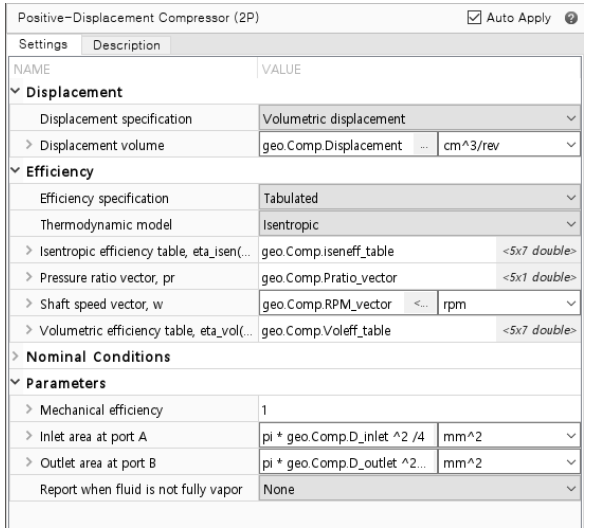
$$\dot{m}_{comp} = \frac{N}{60}\rho_{in}V_D\eta_v$$

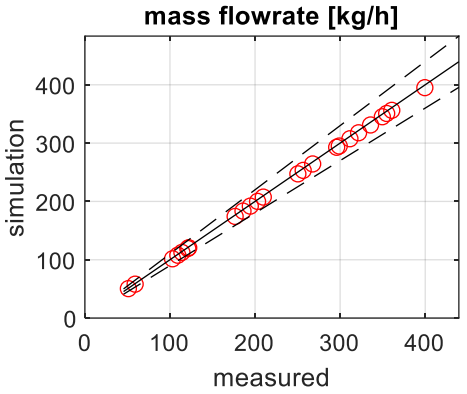
$$P_{flow} = \frac{N}{60}P_{in}V_{in}\left(\frac{n}{n-1}\right)\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{n-1}{n}} - 1\right)$$

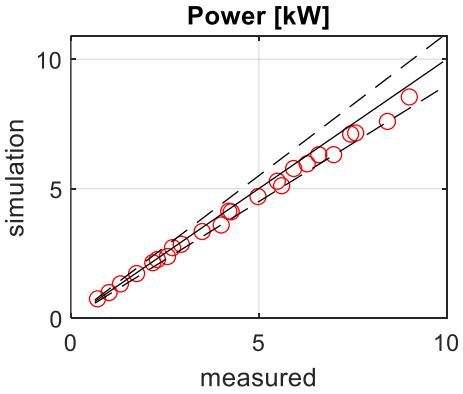
$$P_{comp} = P_{flow}/\eta_k$$

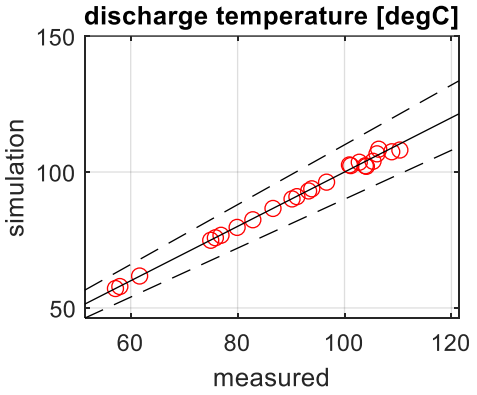
n : *polytropic exponent*

$1 < n \leq \gamma = C_p/C_v$









2. Component Level
- Air & coolant flowrate

Measurement

Table

- Cooling fan
- Blower
- Water pump

Incompressible fluid

$$\dot{m}_{coolant} = f(N_{ewp}, 3WV, T_{coolant})$$

$$P_{ewp} = g(N_{ewp}, 3WV, T_{coolant})$$

Compressible fluid

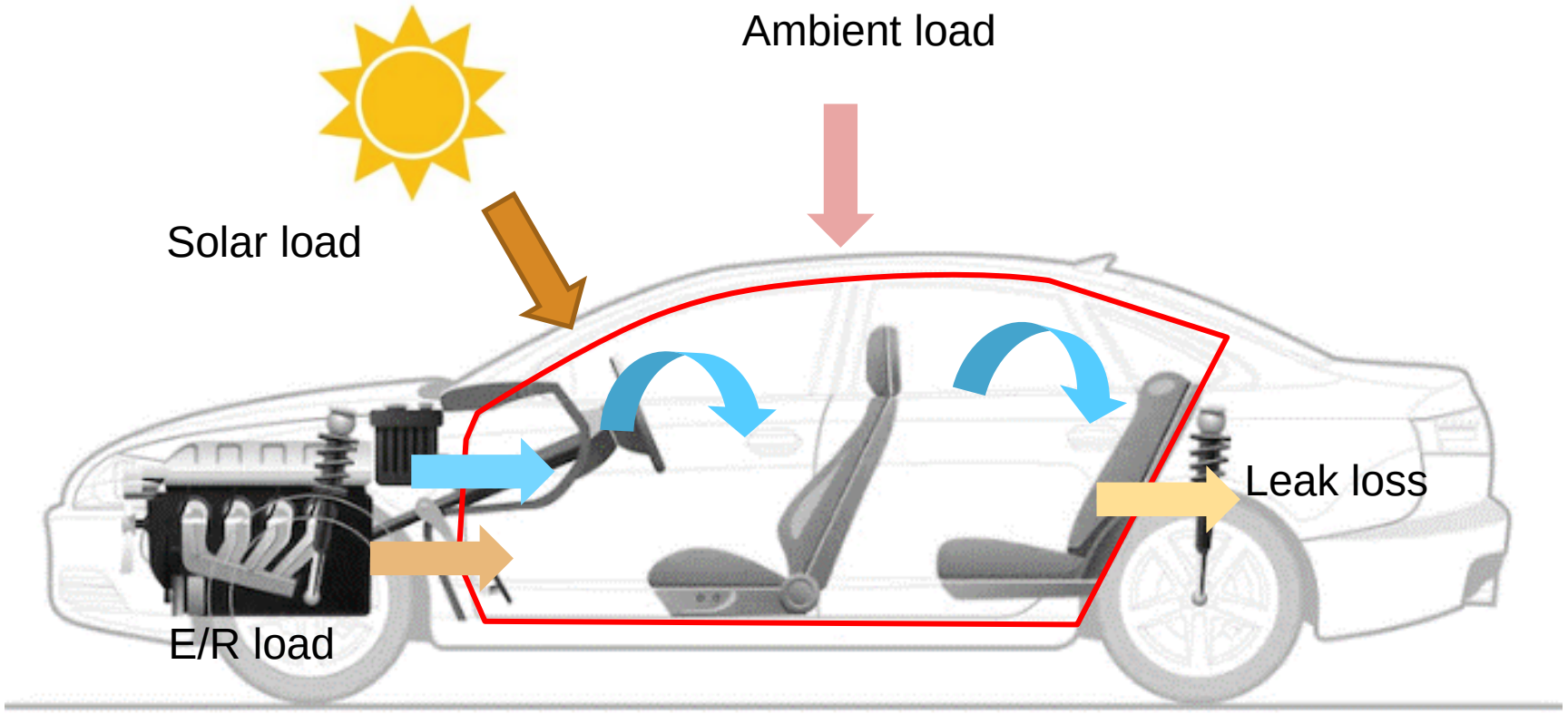
$$\dot{m}_{fan} = f\left(Fduty, V_{speed}, AAF\right)\rho_{air}$$

$$P_{fan} = g\left(Fduty, V_{speed}, AAF\right)$$

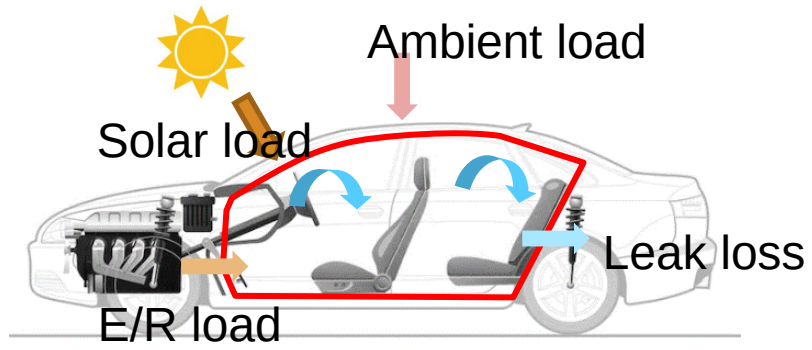
$$\dot{m}_{blwr} = f\left(V_{blwr}, intake, V_{speed}, mode\right)\rho_{air}$$

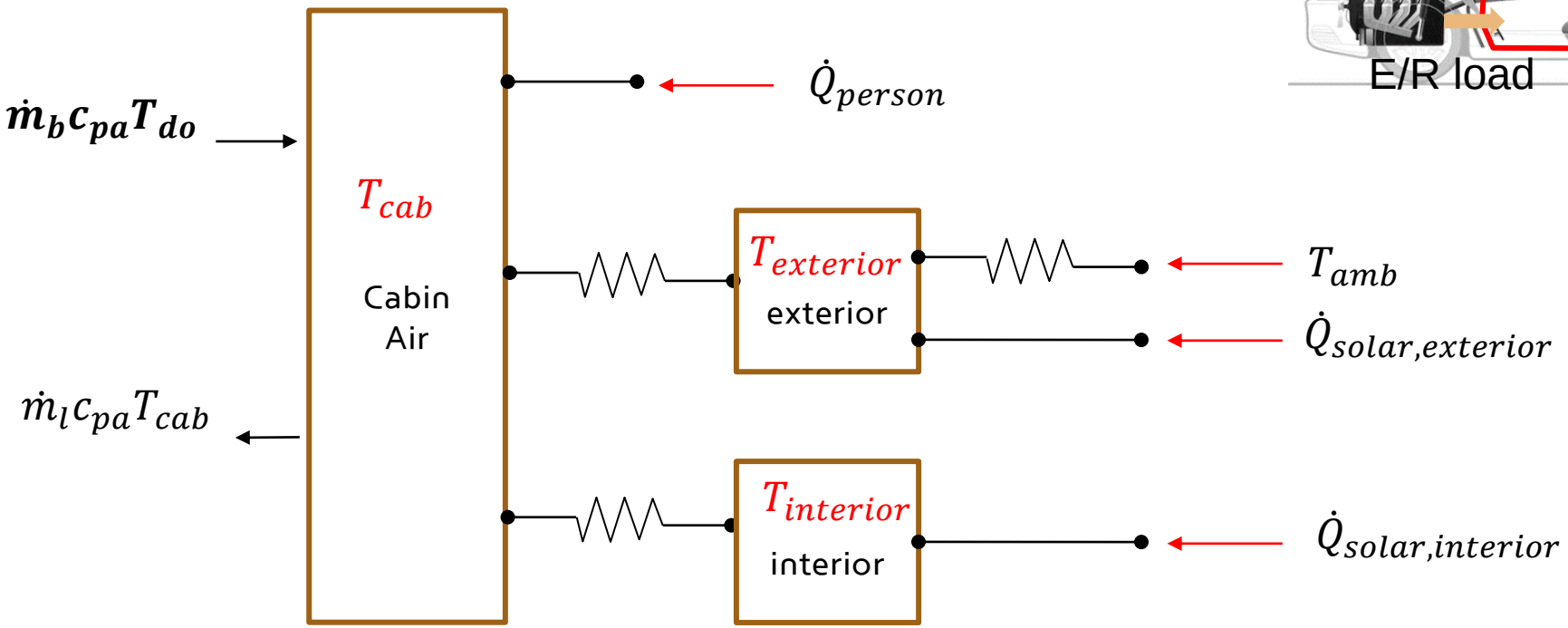
$$P_{blwr} = g\left(V_{blwr}, intake, V_{speed}, mode\right)$$

2. Component Level
- Cabin



2. Component Level
- Cabin





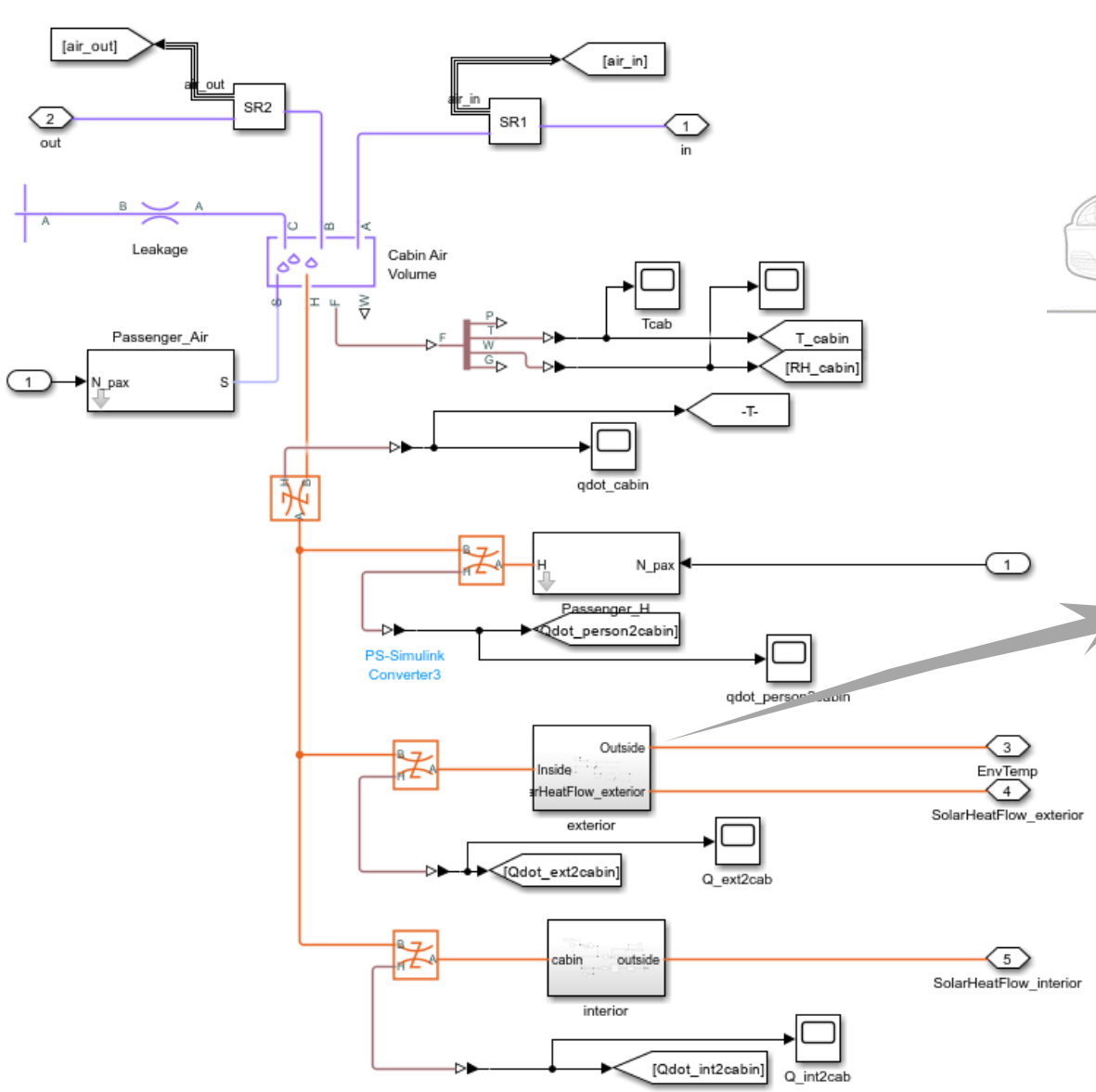
2. Component Level
- Cabin

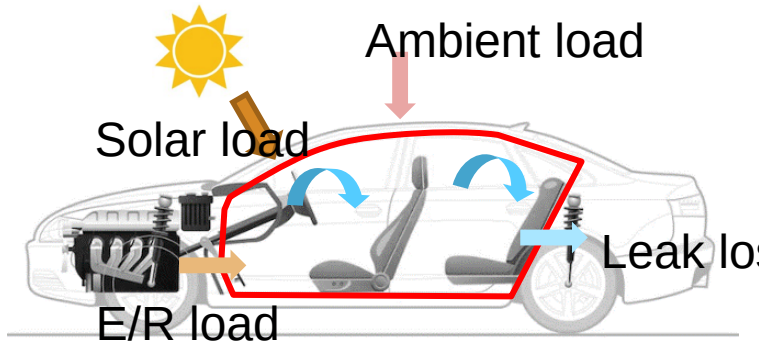
Cabin Air

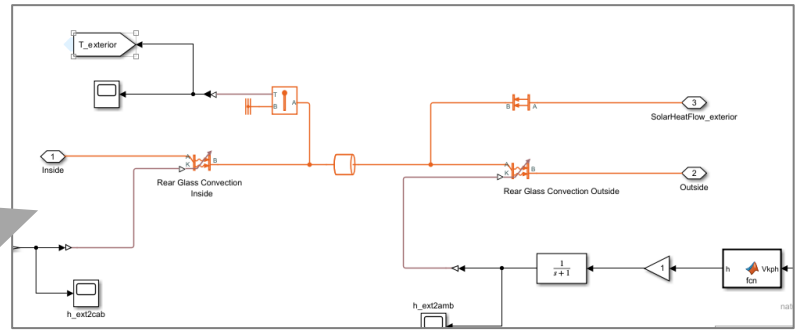
Passenger

exterior

interior







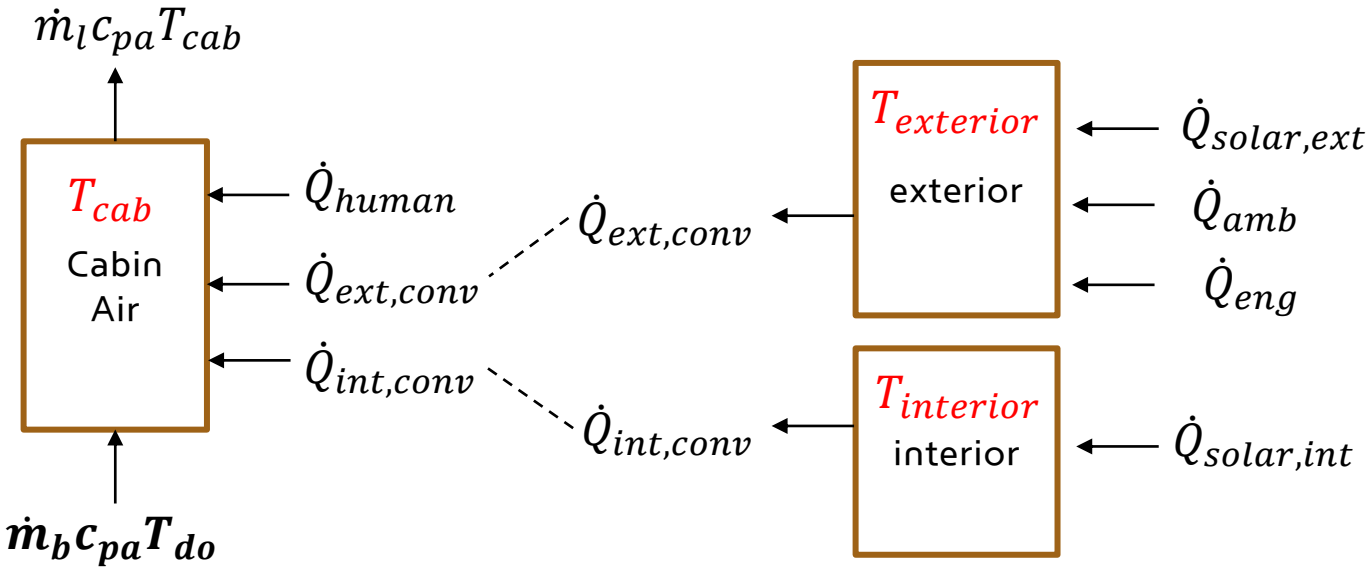
Thermal mass

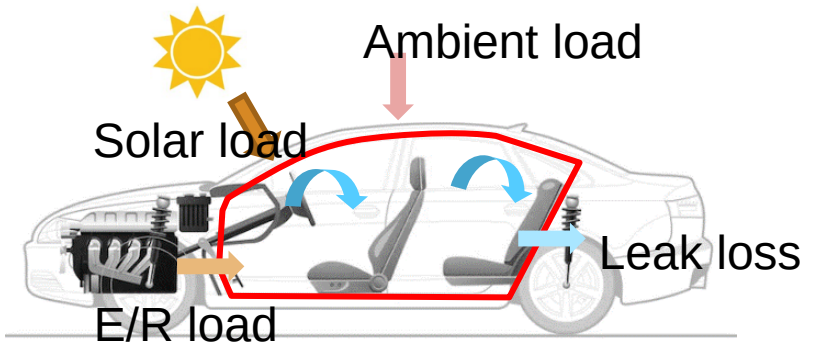
Convective heat transfer

Conductive heat transfer

Radiant heat transfer

2. Component Level
- Cabin





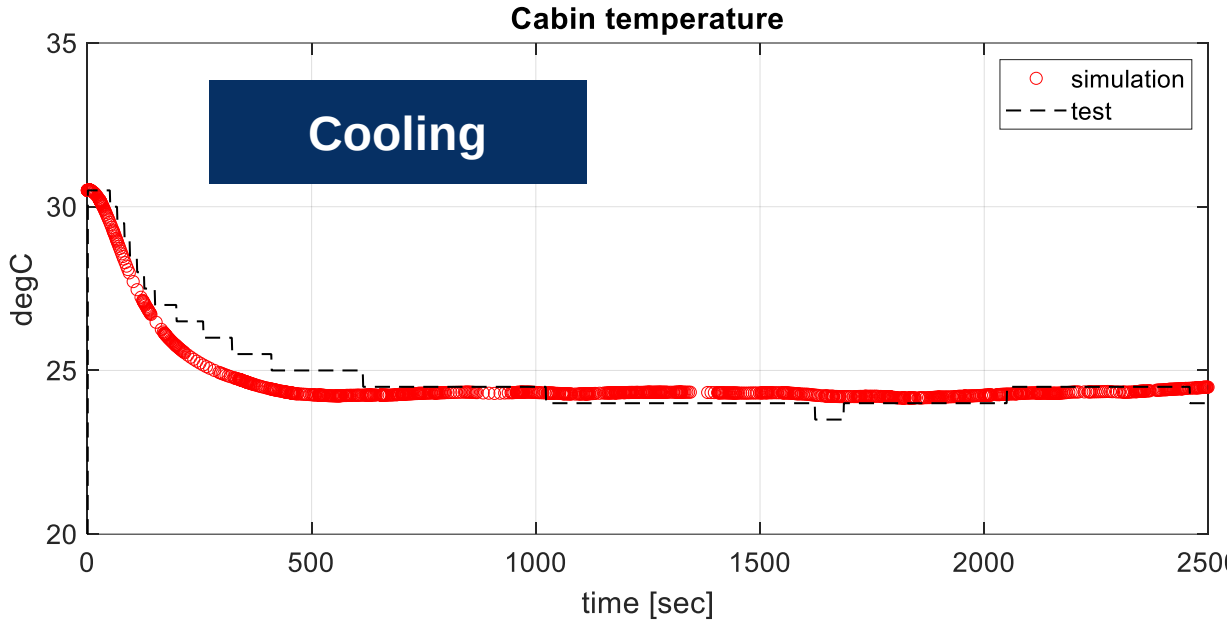
$$MC\frac{dT}{dt} = \sum \dot{Q}_k \qquad \dot{Q} = hA(T_2 - T_1) \qquad \dot{Q} = \frac{kA}{l}(T_2 - T_1)$$

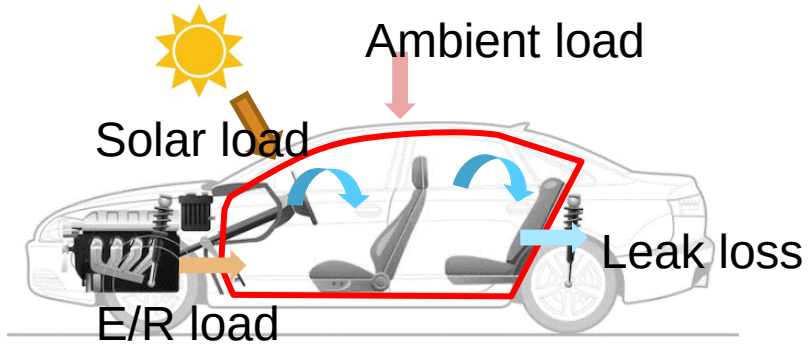
$$\frac{dT_{cab}}{dt} = \frac{1}{m_{cab}c_{p,cab}}\left(\dot{m}_b c_{pa}\left(T_{a,do} - T_{cab}\right) + hA_e(T_{ext} - T_{cab}) + hA_i(T_{int} - T_{cab}) + \dot{Q}_{human} - \dot{m}_{leak}c_{pa}T_{cab}\right)$$

$$\frac{dT_{ext}}{dt} = \frac{1}{m_{ext}c_{p,ext}}\left(\alpha_{s,ext}\dot{Q}_{solar} + hA_{amb}(T_{amb} - T_{ext}) - hA_e(T_{ext} - T_{cab}) + \dot{Q}_{eng}\right)$$

$$\frac{dT_{int}}{dt} = \frac{1}{m_{int}c_{p,int}}\left(\alpha_{s,int}\dot{Q}_{solar} - hA_i(T_{int} - T_{cab})\right)$$

2. Component Level
- Cabin

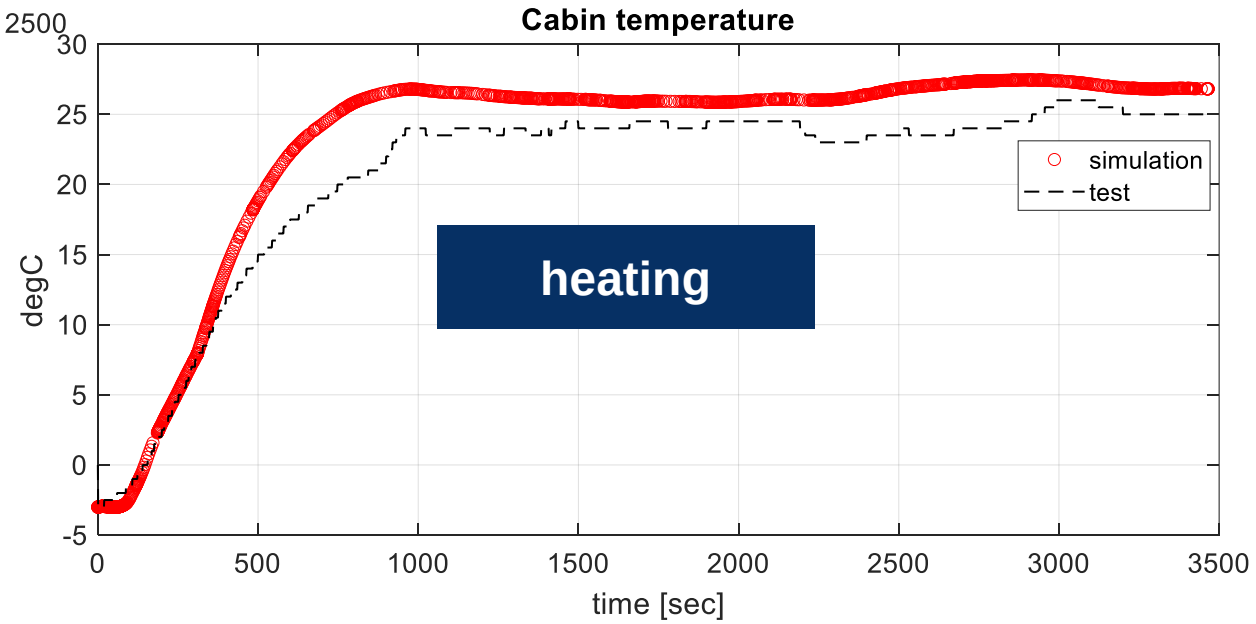




7 parameters

$m_{cab}c_{p,cab}$
$m_{ext}c_{p,ext}$
$m_{int}c_{p,int}$

hA_e
hA_i
hA_{amb}
$h_{s,ext}$
$h_{s,int}$



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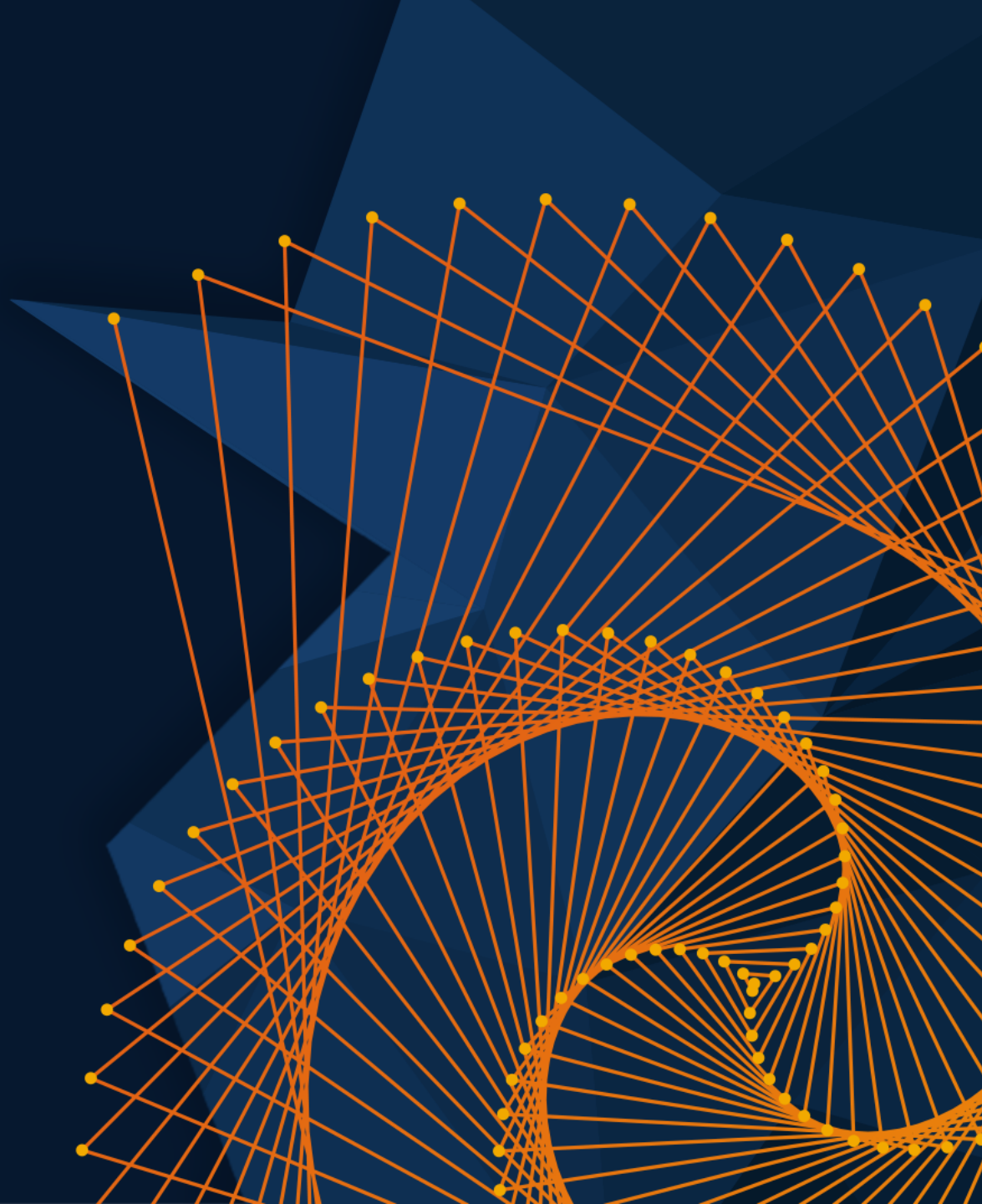
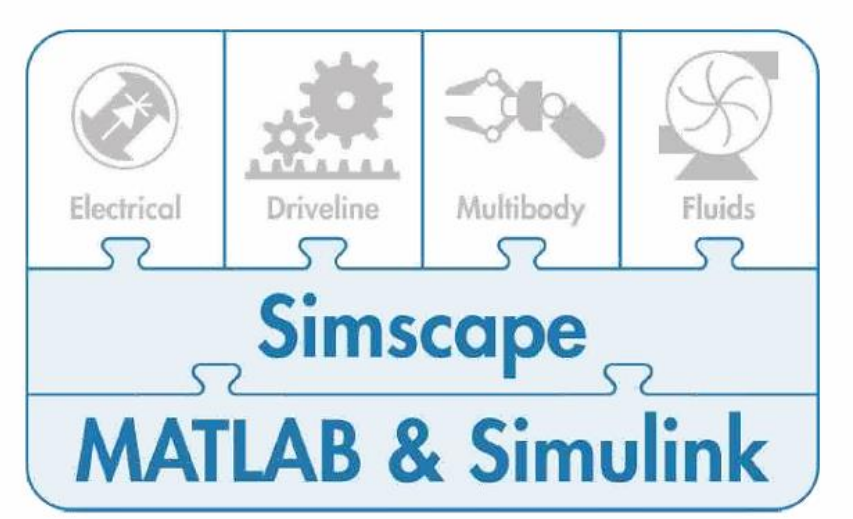


3. System Level
- Plant

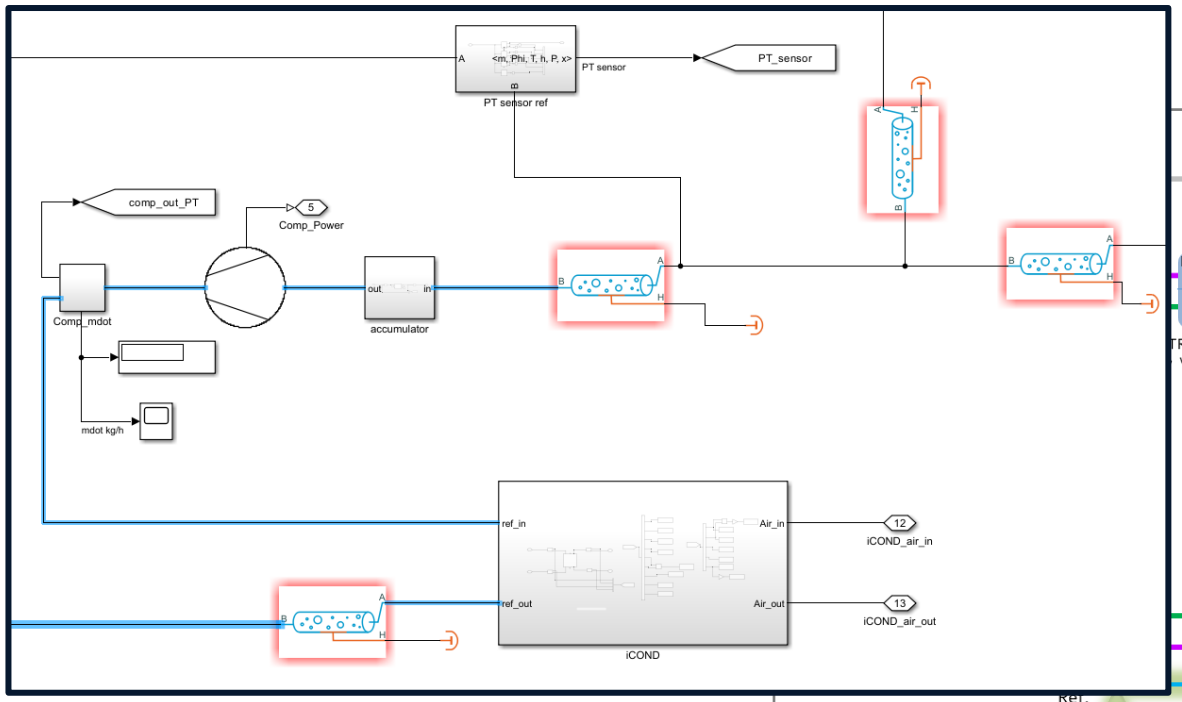


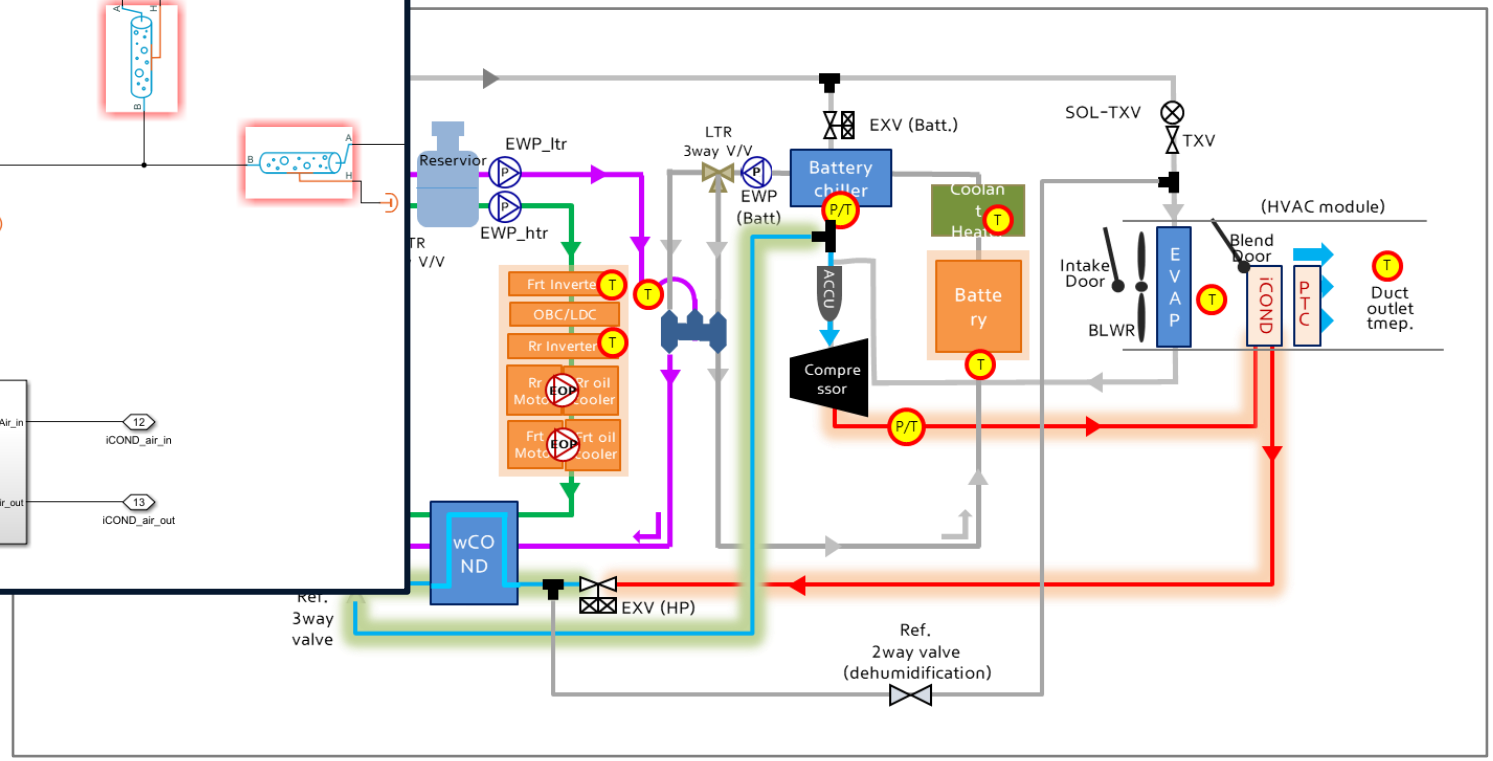
Thermal circuit
- Cooling
- Air conditioning

Simulink & Simscape

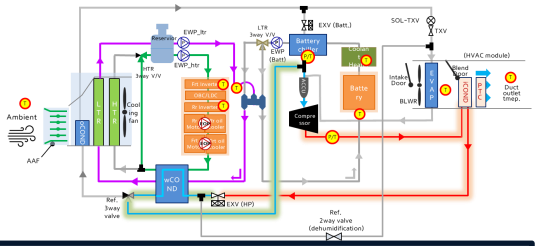
3. System Level
- integration for thermal circuit

Pipe (2P,TL)

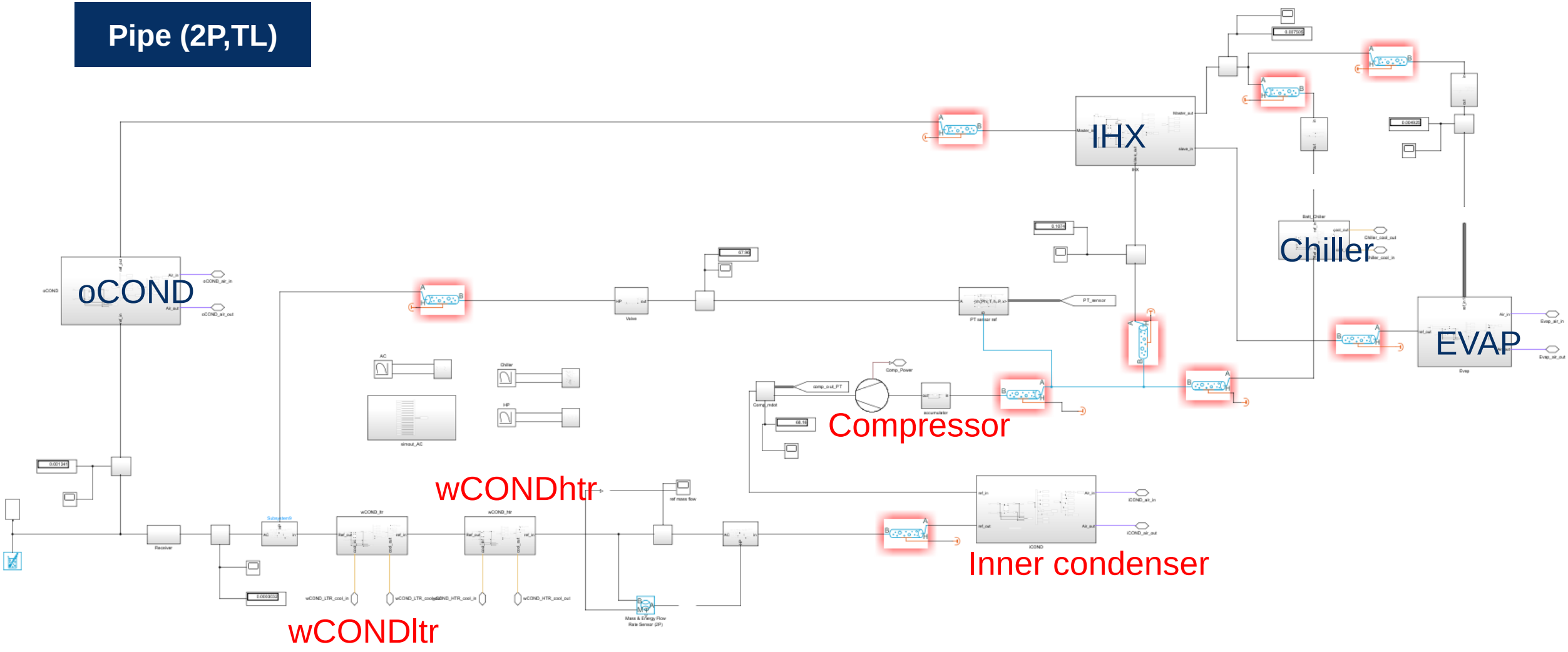




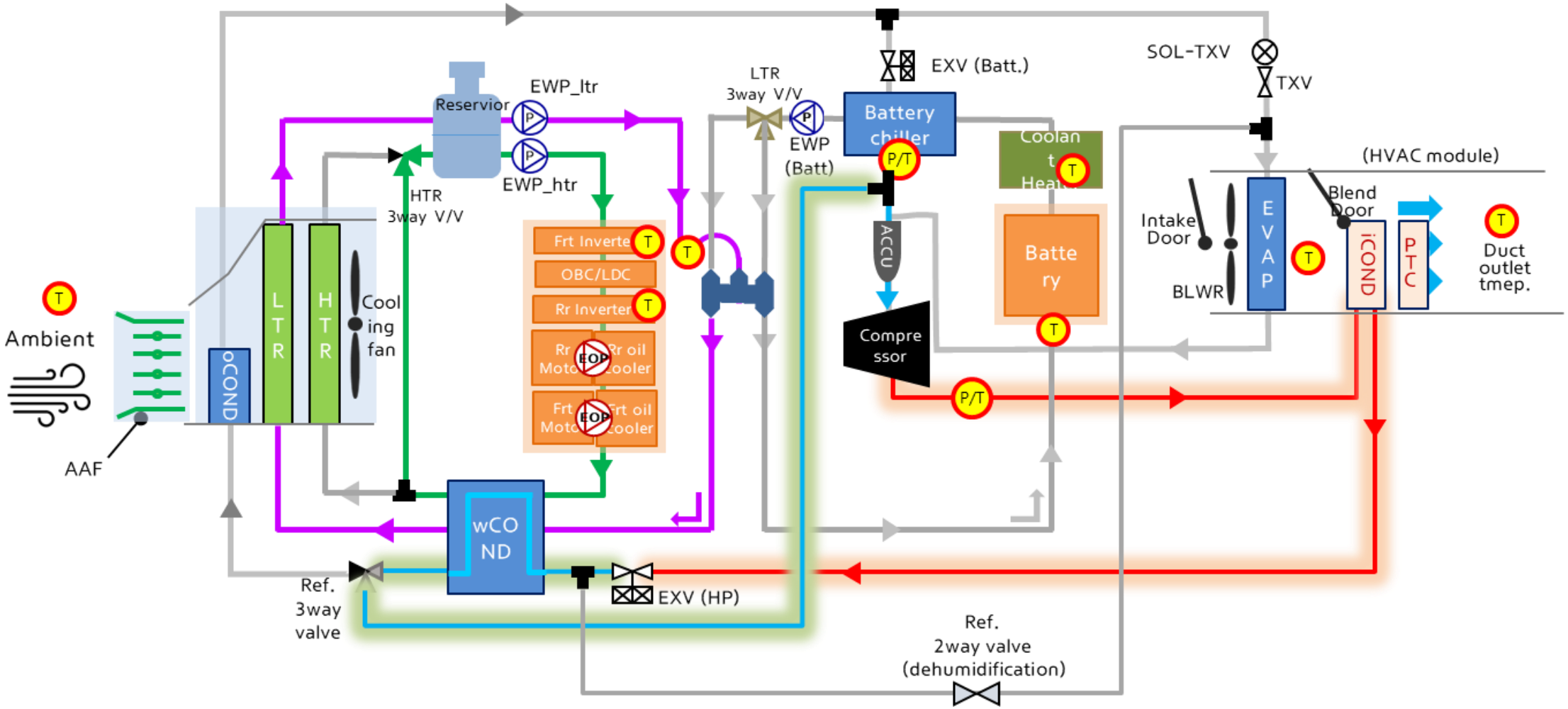
3. System Level
- Heat pump (2P-MA,2P-TL,TXV,EXV,Compressor)



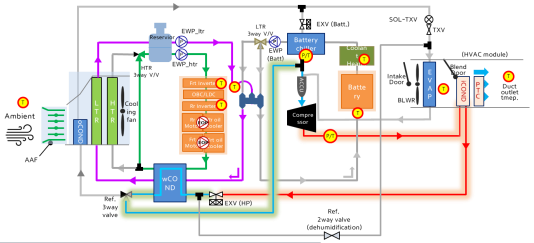
Pipe (2P,TL)

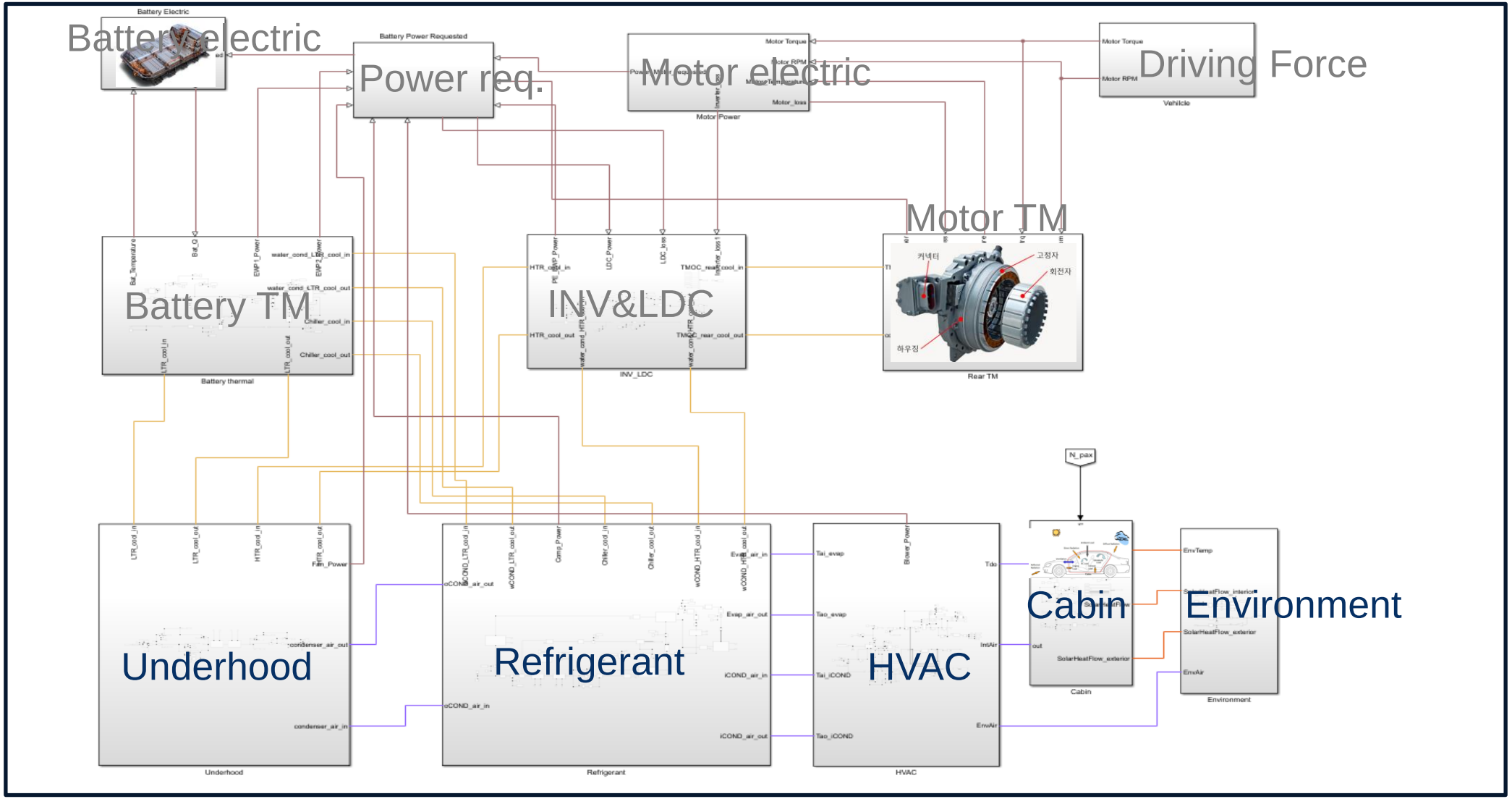


3. System Level
- Thermal circuit



3. System Level
- Thermal circuit





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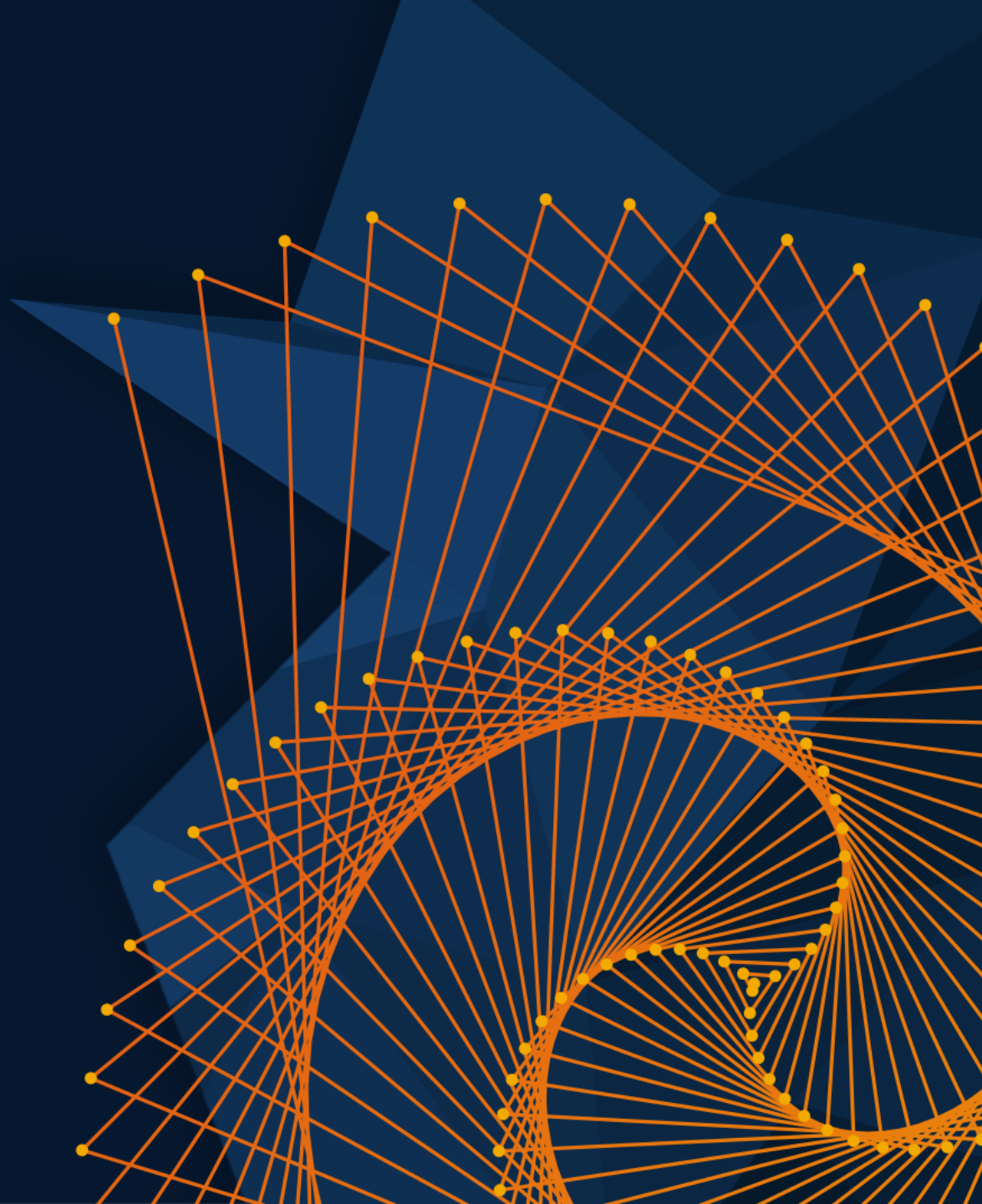
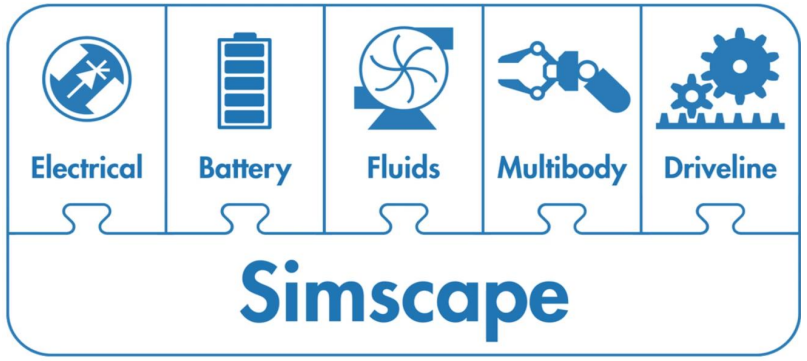
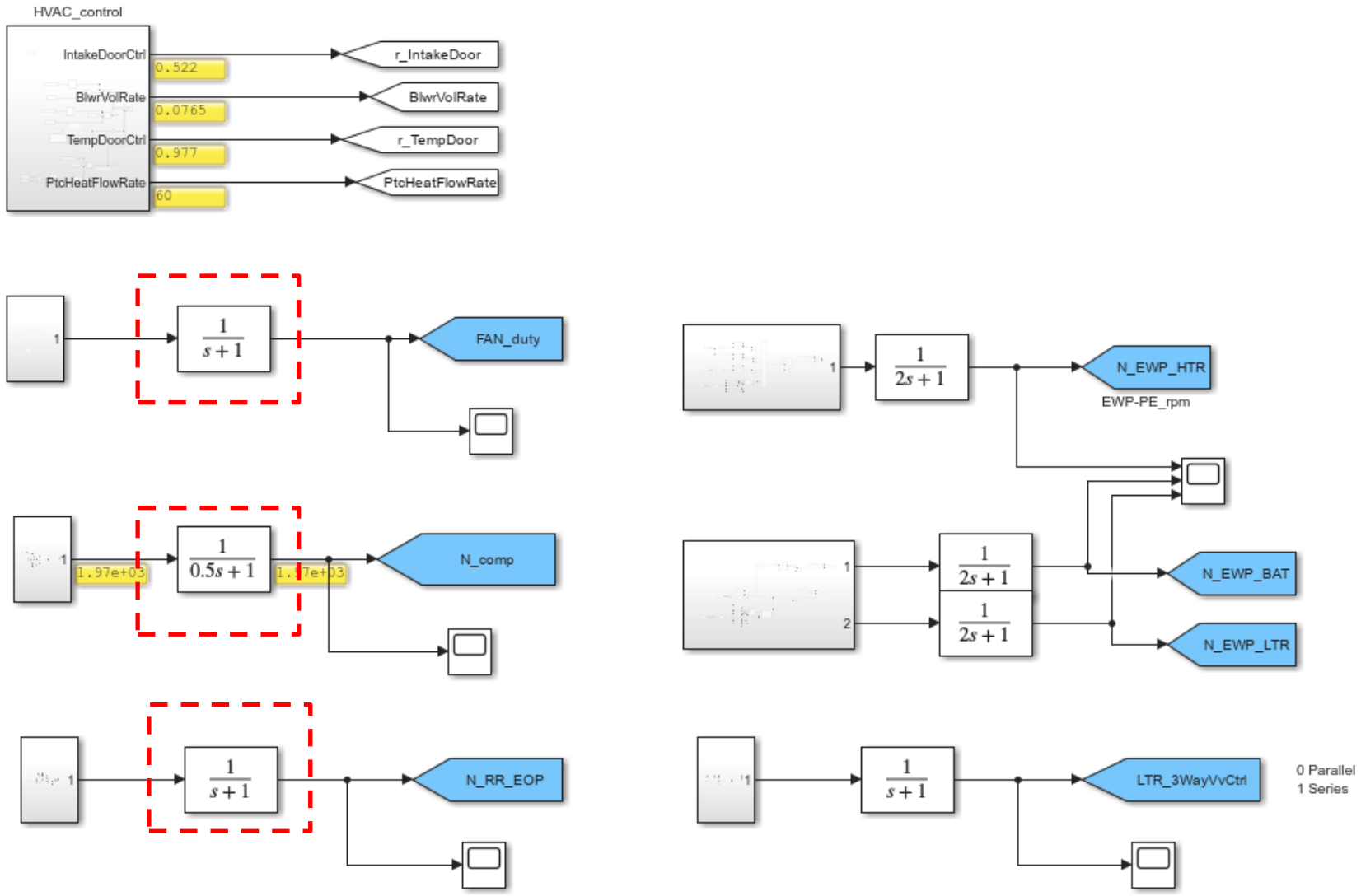


4. Control logic & Verification



Discrete & Continuous
- Plant : continuous
- Controller : discrete ?

4. Control logic & Verification

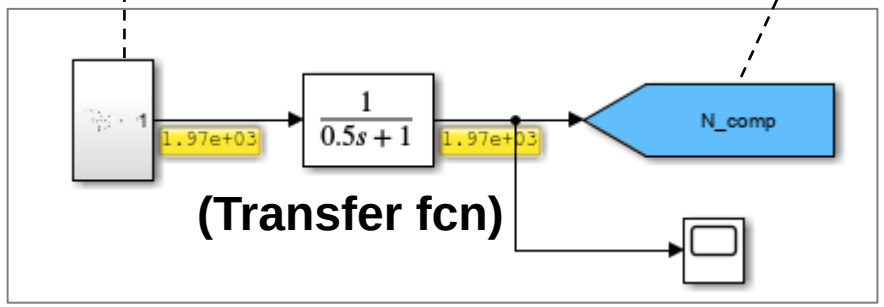


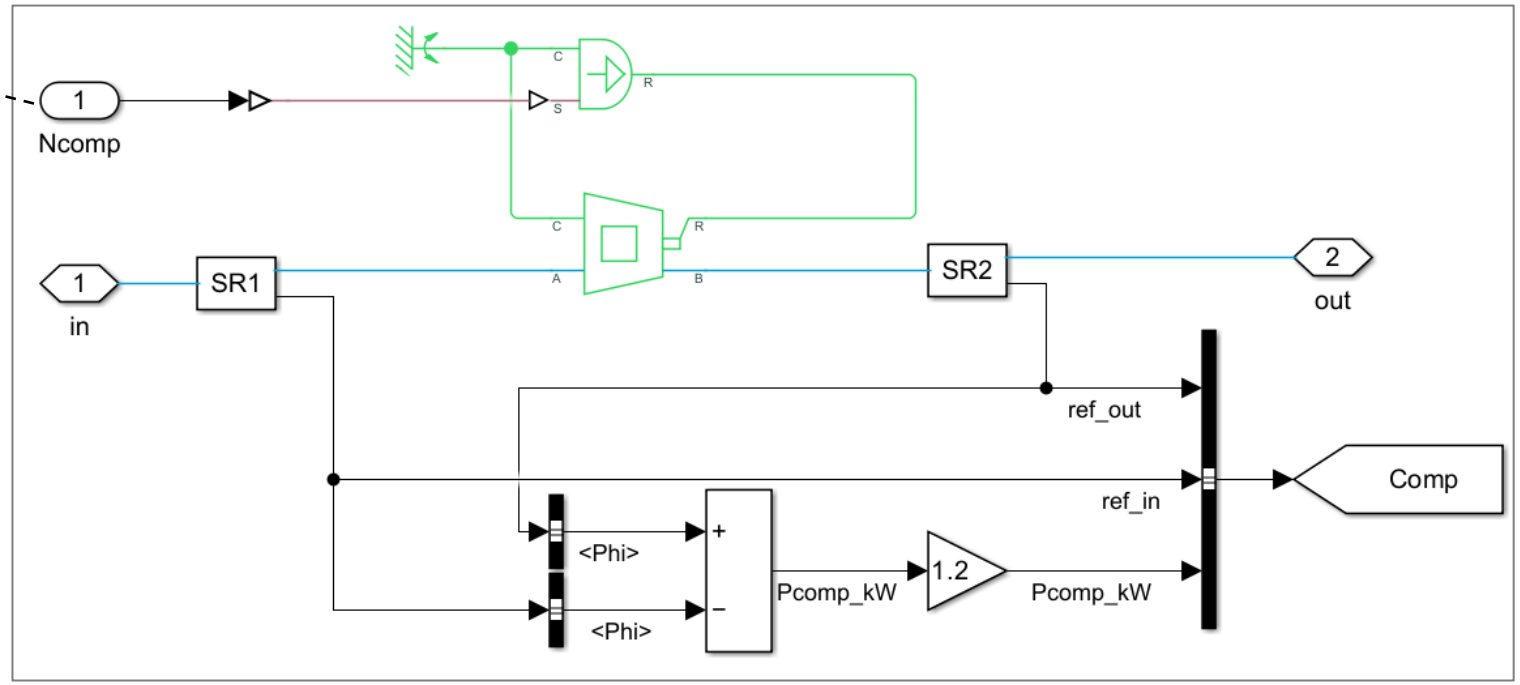
4. Control logic & Verification

Controller

Plant

- Logic : discrete
- Signal : continuous





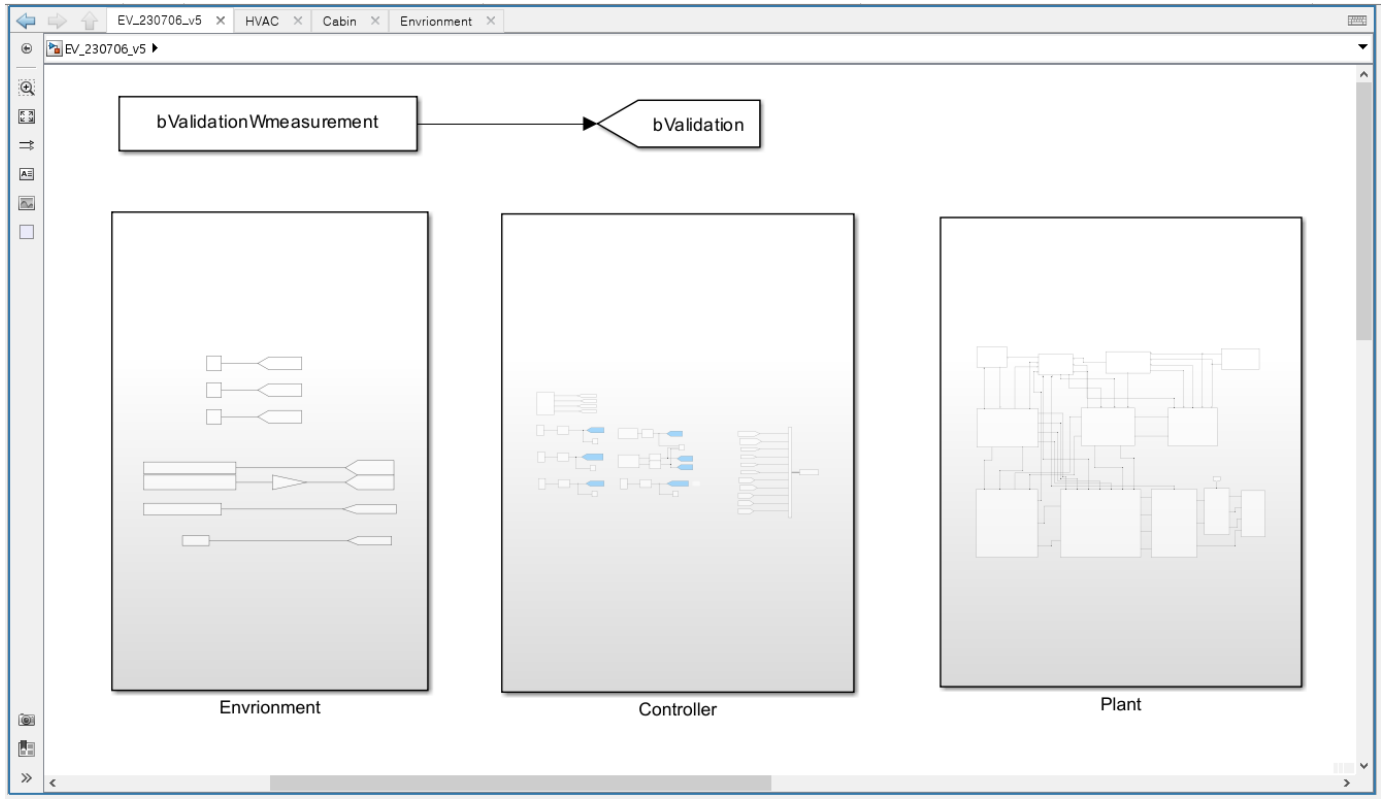
4. Control logic & Verification

Run time

- compile + initializing : 3.5minute + 1.5minute (too slow)
- after then, the simulation time to real time is 1/3

```
Compiling : Analyzing equation systems for Simscape physical networks: Started
```

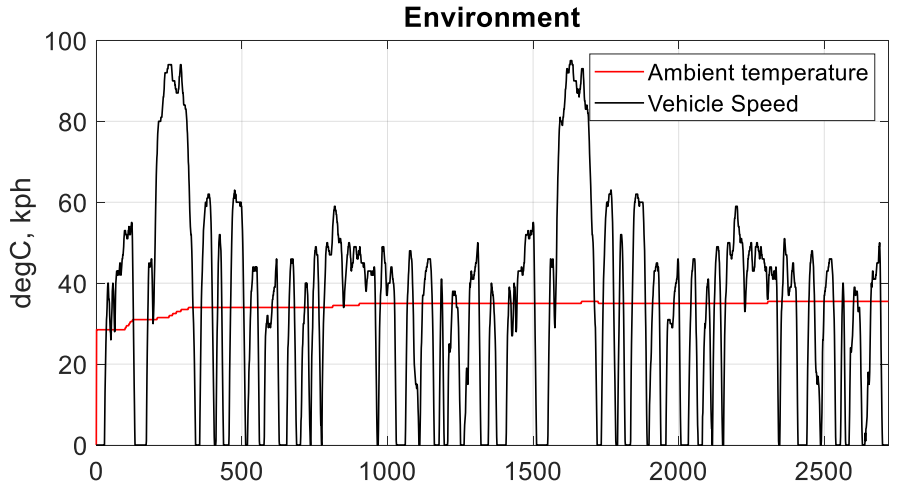
```
Running : Initializing equation systems for Simscape physical networks: Started
```

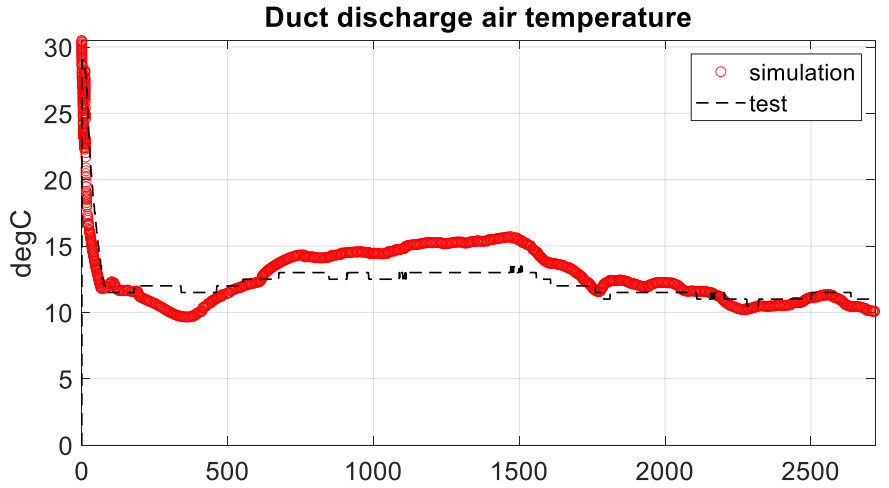


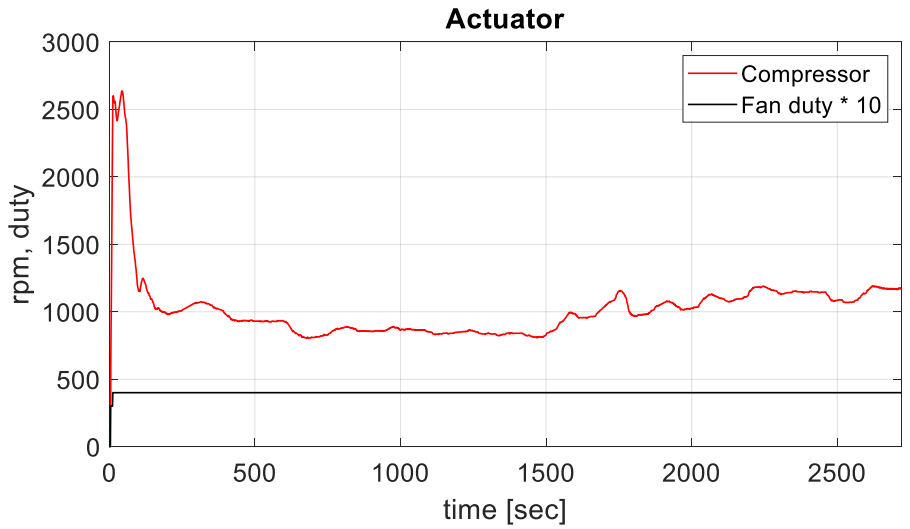
4. Control logic & Verification

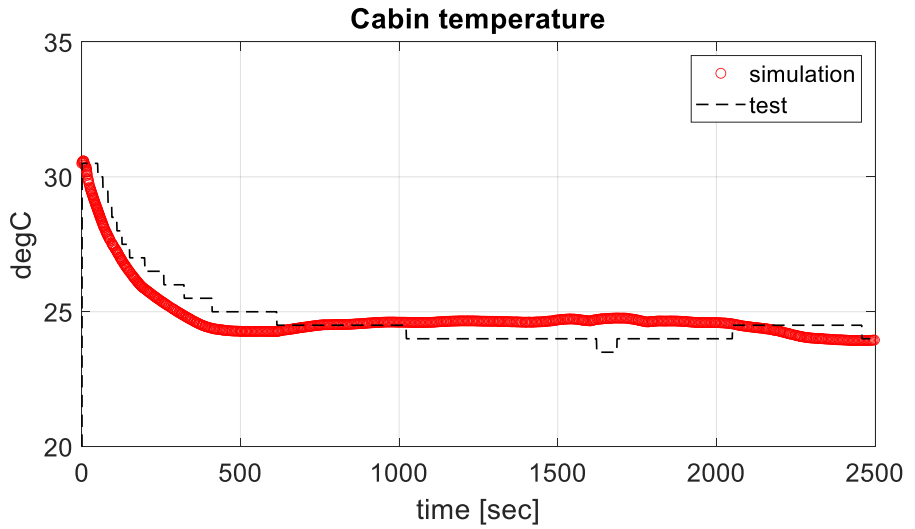
- Control input based on experiment
  : Compressor, cooling fan, EWP, TXV

Simulation (Cooling mode around 35℃, 850W/m^2)





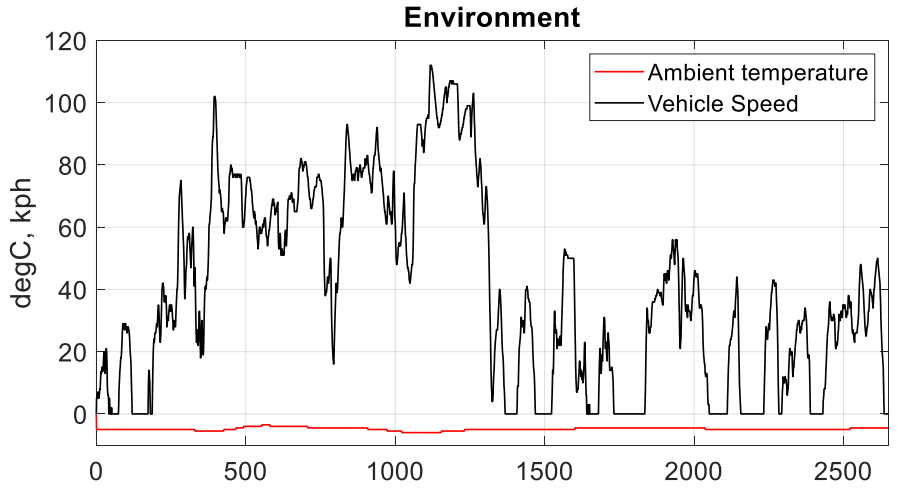


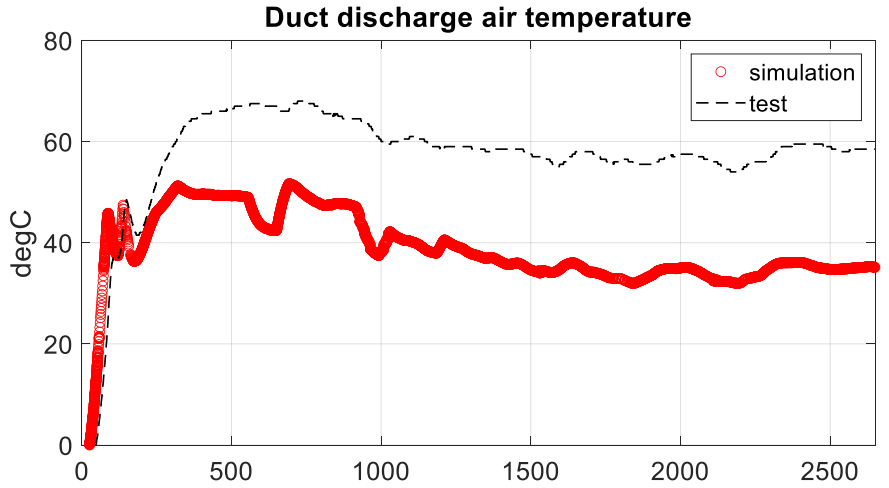


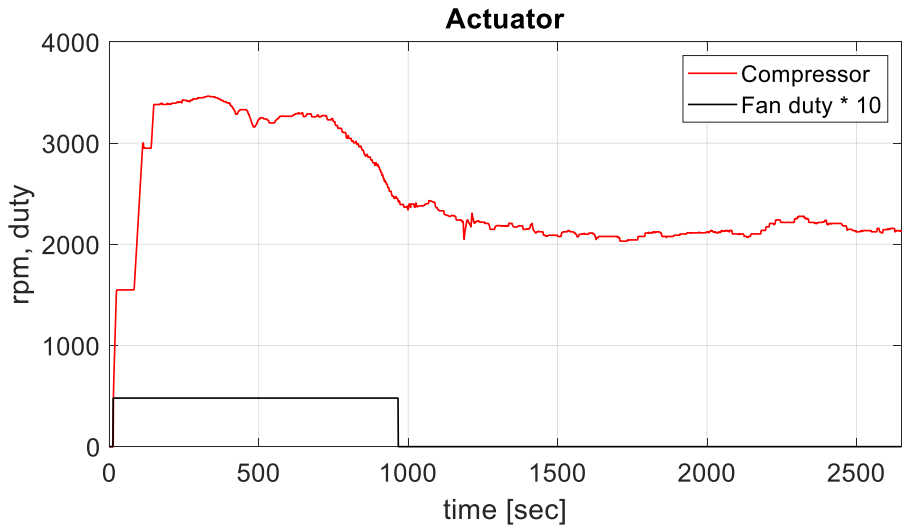
4. Control logic & Verification

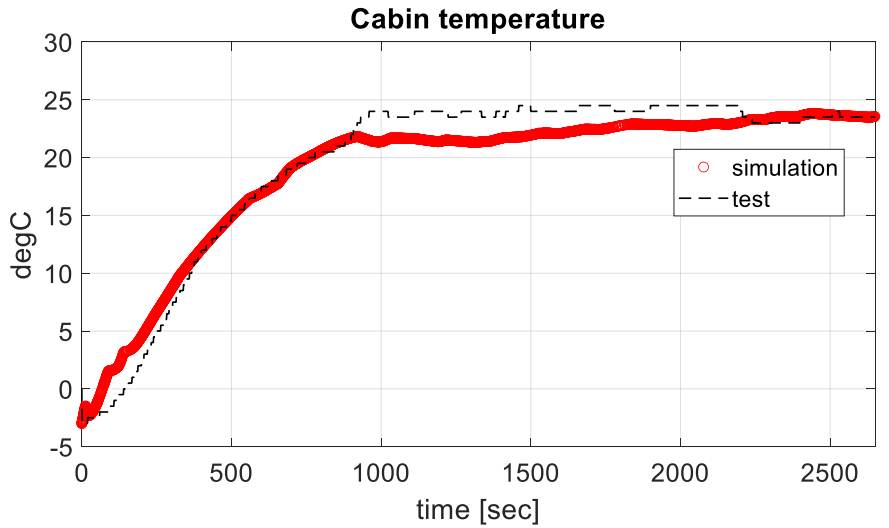
- Control input based on experiment
  - except : EXV (SH control)

Simulation (Heating mode around -5℃, cloudy)









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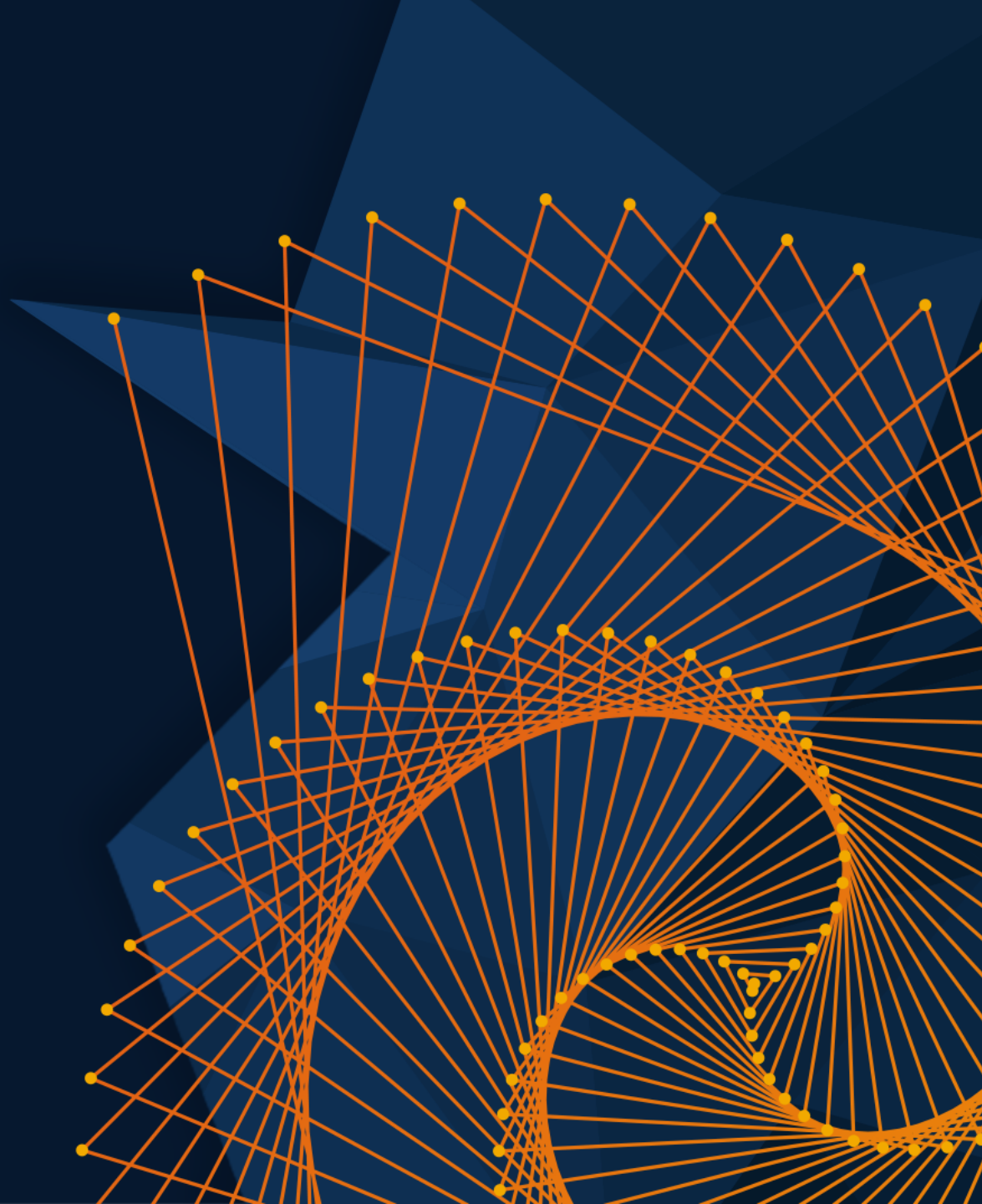
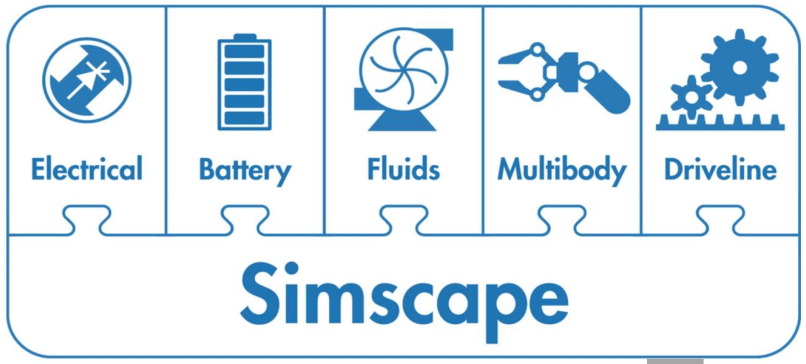
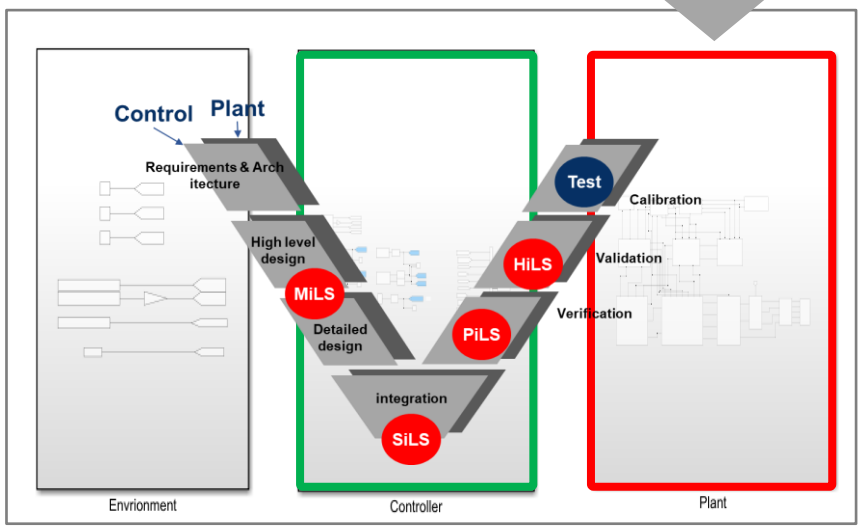


5. Conclusion





1. Component & System level using simscape
   - Heat Exchanger : TL-MA, TL-2P, 2P-MA
   - Compressor, Cabin
   - Integration for thermal circuit & Tube pipe

2. Control logic for simscape
   - Discrete signal – Transfer fcn – Continuous signal

3. Virtual Plant (simscape) with controller
   - Virtual plant performance → thermal circuit, size decision
   - Logic performance → advanced control logic development
   - Various physical data