244th ECS MEETINGS
10A-1704

Performance Analysis of Non-Humidified High-Temperature PEFC by Fuel Cell System Simulator

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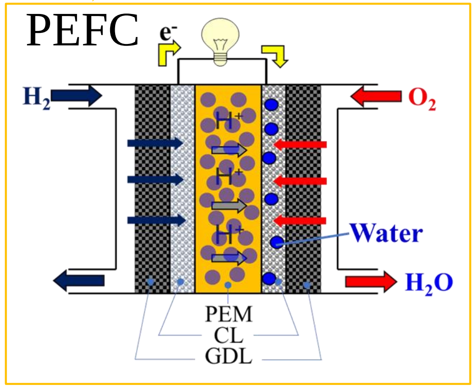
■ Polymer Electrolyte Fuel Cell (PEFC)

・Excellent start-ability and load followability

・FCEV is in practical use

＊) https://toyota.jp/mirai/



Various applications

＊) https://www.toyota.co.jp/fuelcells/jp/applications.html

Huge development costs / Short of evaluation time

MBD※ by **FC system simulator**

※Model Based Development

Severe usage

Heavy Duty Vehicles (HDVs) are required **high load** operation

Insufficient cooling capacity

Cooling capacity： $Q_{cool} = A \cdot K \cdot \Delta T$

A：Radiator size

K：Overall heat transfer coefficient

$\Delta T = T_{FC} - T_{amb.}$

T_{FC}: ～100℃ $T_{amb.}$: about 30℃

Conventional PEFC：Small ΔT

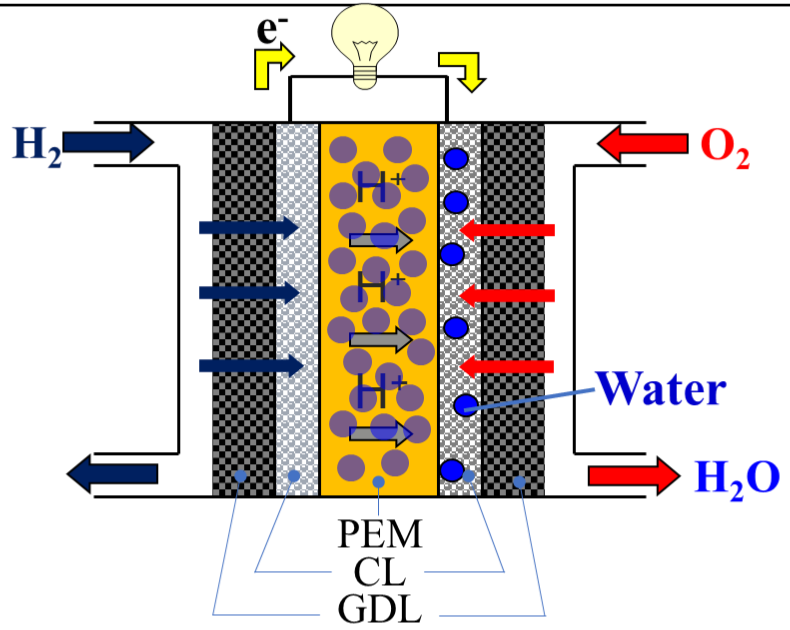
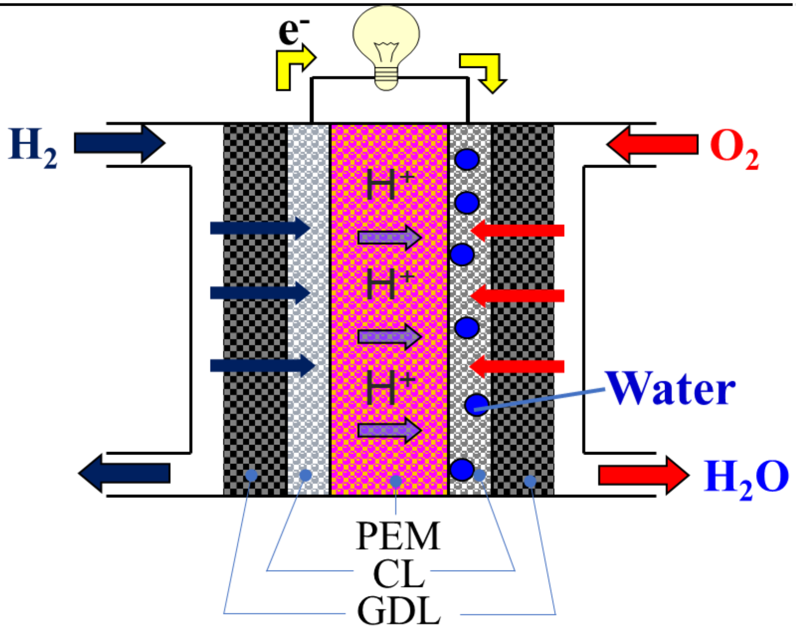
Nafion© based membrane is widely used

(over 100°C)

High-Temp. PEFC (HT-PEFC) is expected： **Large ΔT**

HT-PEFC is needed for widespread use of Fuel Cell

Basic principle of HT-PEFC

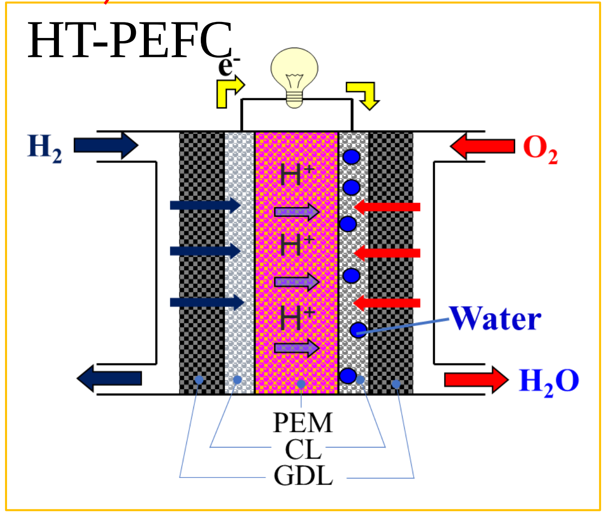
	Conventional-PEFC e.g. Nafion©	HT-PEFC e.g. PBI
Operating condition	**～100°C** Humidification is required. **Dry-out** occurs above 100°C.	**～200°C** H+ conduction is possible under **non-humidified** condition.
H^+ conducting path	Sulfonic acid + **Water**	doped **Phosphoric acid**
Structure of MEA		

H^+ is conducted under non-humidified condition
→ High temp. operation is possible

Objective

*) https://www.toyota.co.jp/fuelcells/jp/applications.html

Appling in this study



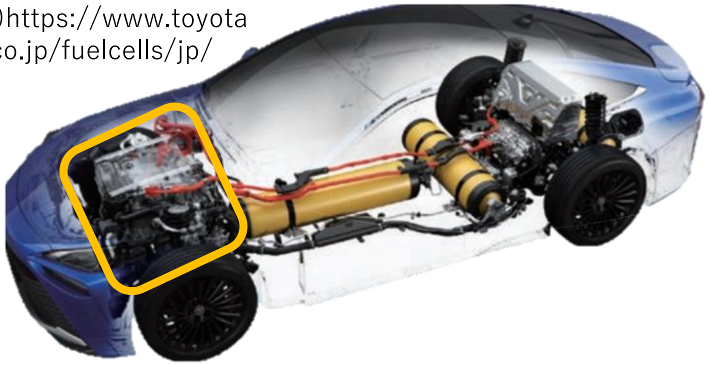
Objective

Evaluating the **HT-PEFC**'s utility for **HDV** by **FC system simulator**, especially its **cooling** performance

FC-DynaMo[1,2,3]

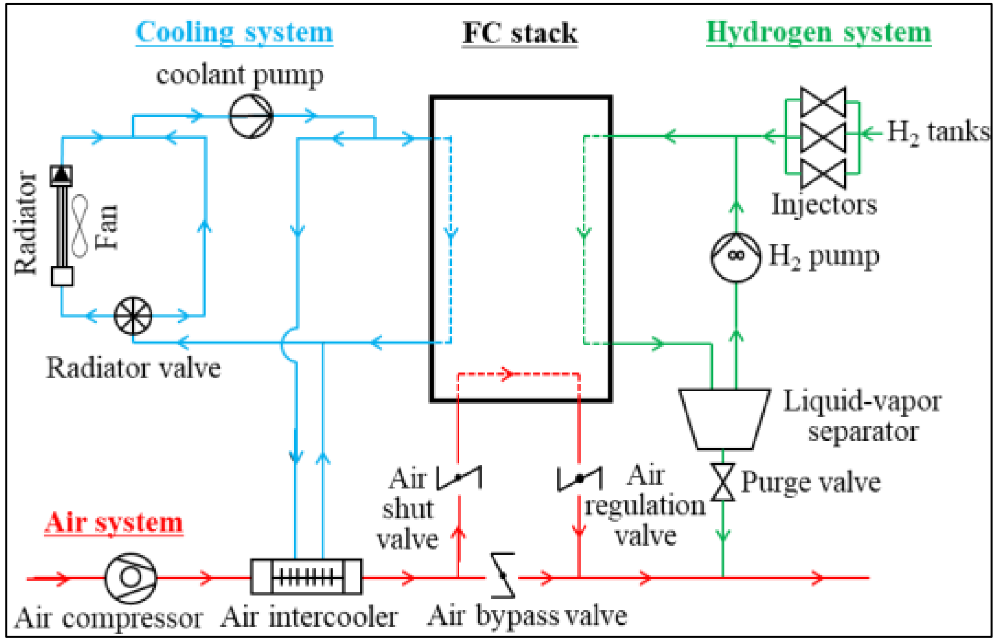
- Based on data obtained from TOYOTA Gen.2 MIRAI

*)https://www.toyota.co.jp/fuelcells/jp/



FC stack, **hydrogen system**, **air system**, and **cooling system** are modeled

➡ Possible to simulate unsteady vehicle driving



(1) S. Hasegawa et al., *ECS Transactions*, 104, 3-26 (2021).
(2) S. Hasegawa et al., *ECS Transactions*, 109, 15-70 (2022).
(3) S. Hasegawa et al., *Comput. Aided Chem. Eng*, 49, 1123-1128 (2022).

Developed by NEDO(※)'s project
※New Energy and Industry Technology Development Organization, Japan

Evaluating HT-PEFC system for HDV by FC-DynaMo

Outline

(1) Simulation results of conventional system
☞ Necessity of HT-PEFC

(2) Construction of oil cooling system

(3) HT-PEFC's IV performance and simulation results

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(1) Simulation results of conventional system

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(2) Construction of oil cooling system

(3) HT-PEFC’s IV performance and simulation results

Target : Vehicle class and driving pattern

■ Using driving data of engine vehicle in the U.S.(4)

(4) C. Zhang, et al, *Transportation Research* Part D 95, (2021), 102843.

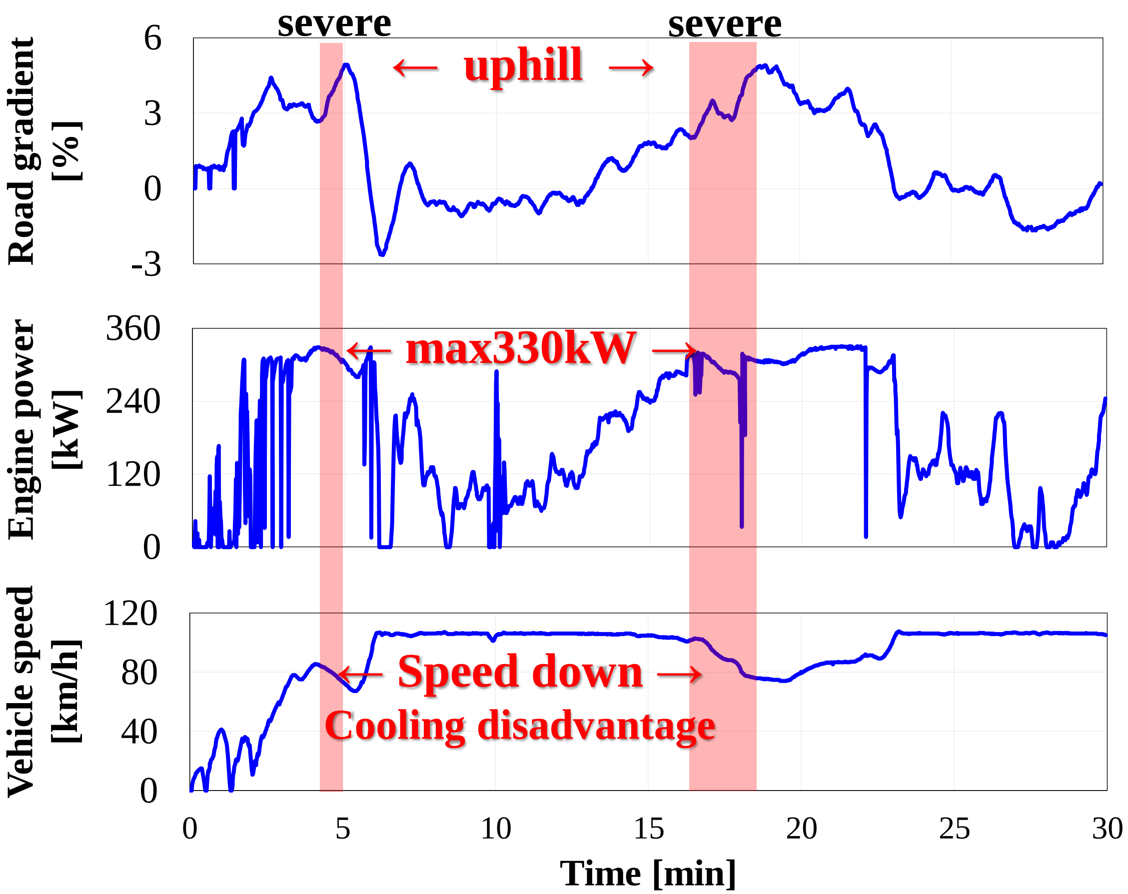
Target vehicle class

Class 8 (HDV)

＊) https://www.volvotrucks.us/trucks/vnl/

Target driving pattern

Long-haul dairy trip including **uphill roads**



Analyzing the most severe usage for HDV

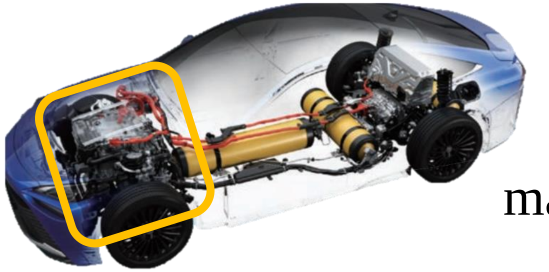
FC system for HDV

■ Using **FC-DynaMo**(1,2,3)

(1) S. Hasegawa et al., *ECS Transactions*, 104, 3-26 (2021).
(2) S. Hasegawa et al., *ECS Transactions*, 109, 15-70 (2022).
(3) S. Hasegawa et al., *Comput. Aided Chem. Eng*, 49, 1123-1128 (2022).

・Based on data obtained from **TOYOTA Gen.2 MIRAI**

*) https://www.toyota.co.jp/fuelcells/jp/



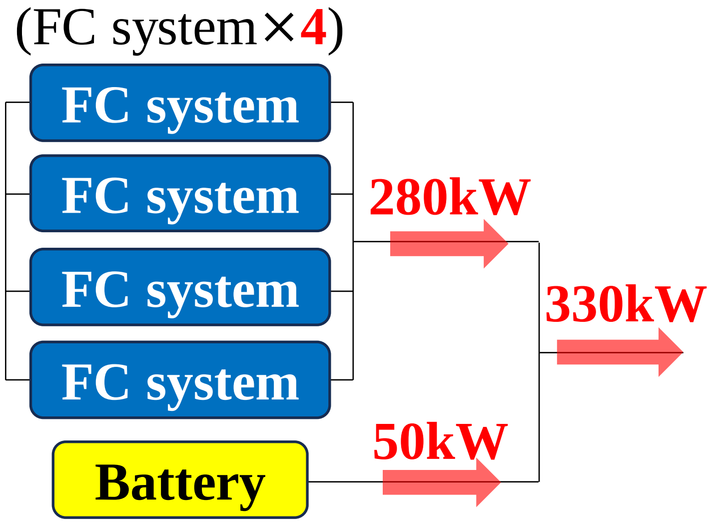
max **100kW**

Multiplication of FC systems → **w/ Battery**

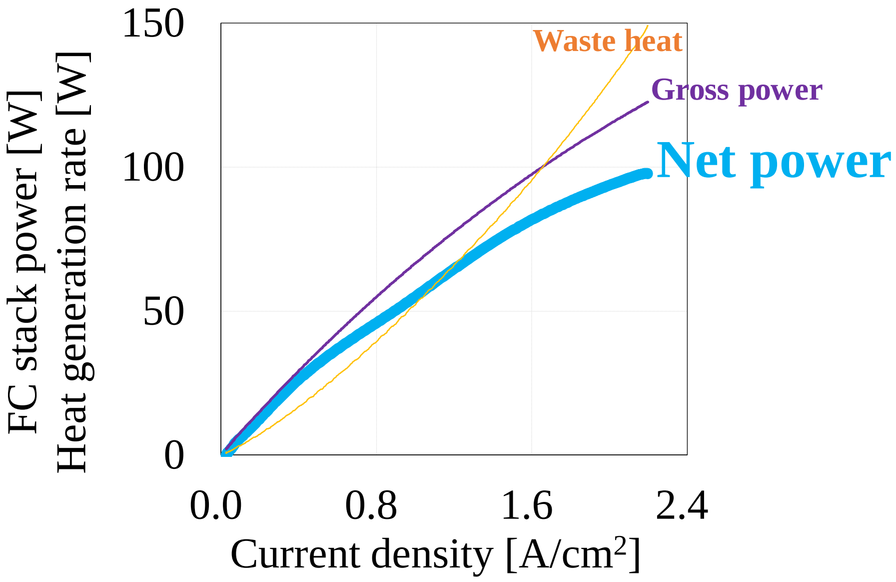
■ HDV

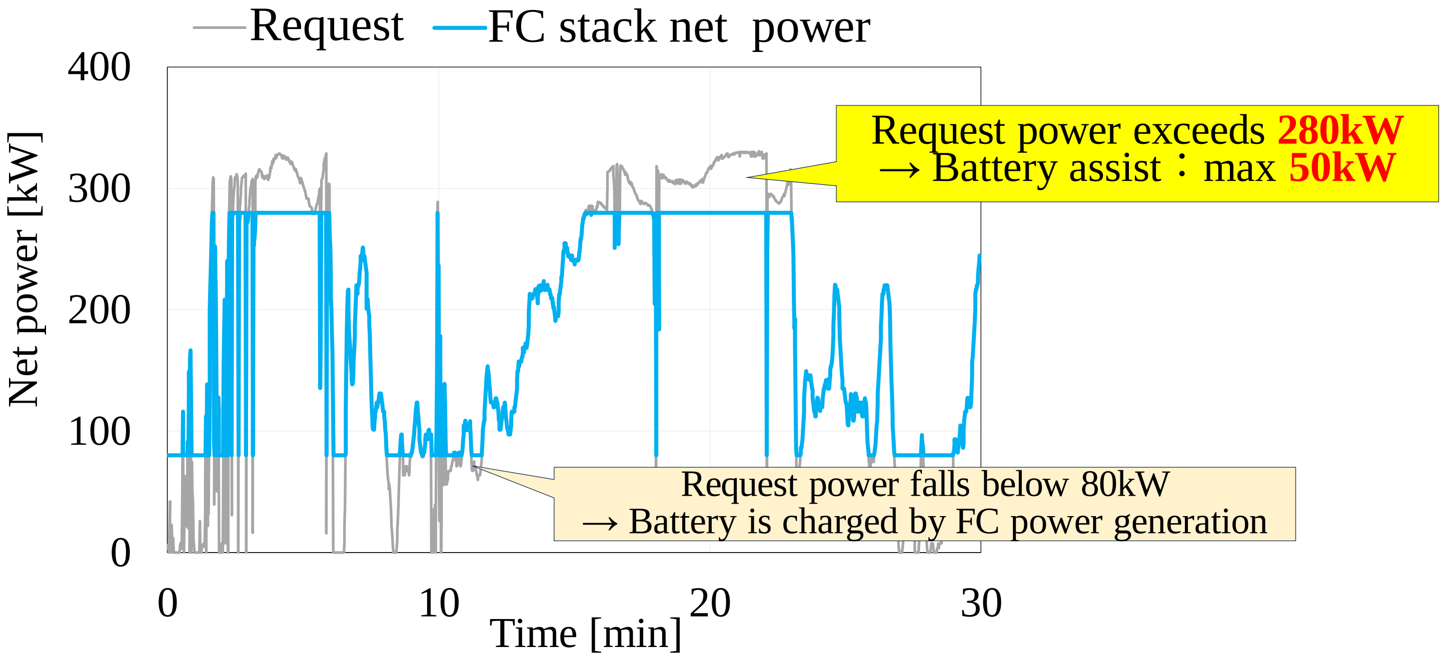
＊) https://www.volvotrucks.us/trucks/vnl/

Request：max **330kW**



■ FC stack's net power and heat generation



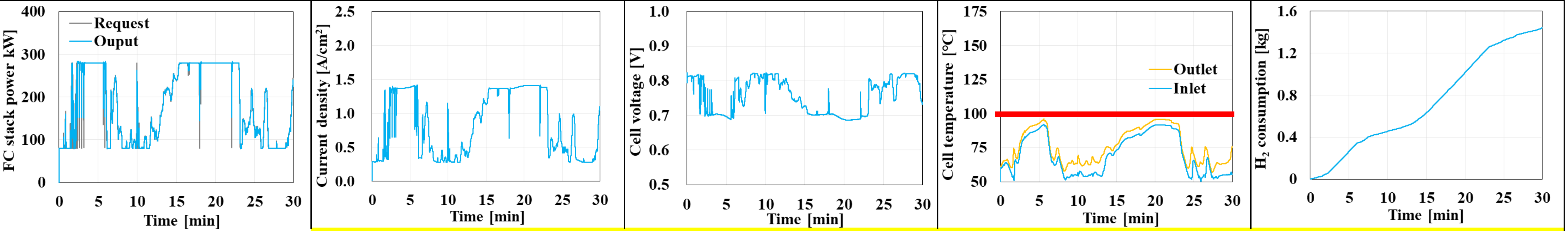


Introducing 4-FC systems and battery assist for HDV

HDV driving simulation results by FC-DynaMo

■ Using MIRAI-MEA (**Conventional MEA**)

Radiator size	FC stack net power	Current density	Cell voltage	Cell temp.	H_2 consumption
[Ref.] MIRAI × 4 (A=1.28m²)					



Possible to drive below 100°C

Cooling capacity [W]

$$Q_{cool} = A \cdot K \cdot \Delta T$$

- A : **Radiator size** [m²]
- K : Overall heat transfer coefficient [W/(m²・K)]
- ΔT : $T_{FC} - T_{amb.}$ [K]

＊) https://toyota.jp/mirai/

(FC system × 4)

- FC system
- FC system
- FC system
- FC system

(0.32m² × 4)

(5) A. Hosoi and K. Inui, *Transactions of Society of Automotive Engineers of Japan*, 52, 142-147 (2021).

(6) D.T. Hountalas, et al., Energy Conversion and Management, 53, 19-32 (2012).

Engine HDV

Ref. size = **1.28m²** → **Target** size = **0.83m²**

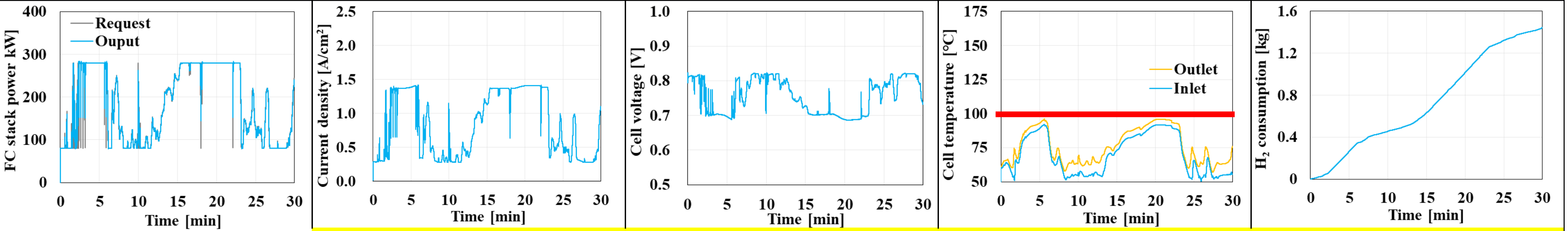
HDV w/conventional PEFC is possible to drive below 100℃

HDV driving simulation results by FC-DynaMo

■ Using MIRAI-MEA (**Conventional MEA**)

Radiator size	FC stack net power	Current density	Cell voltage	Cell temp.	H_2 consumption

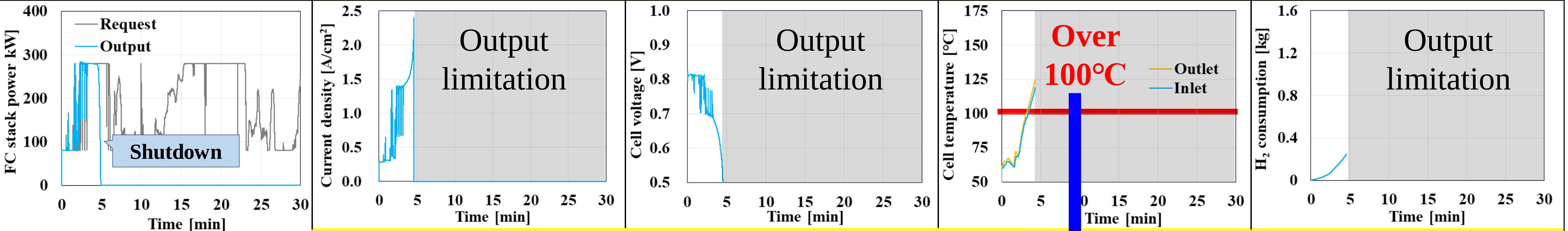
[Ref.] MIRAI × 4 ($A=1.28 m^2$)



Possible to drive below 100°C

↓

[Target] Engine HDV ($A=0.83 m^2$)



Overheating when climbing a hill → Unpossible to drive

<u>Conventional PEFC w/target radiator size results in insufficient cooling</u>

Conventional FC coolant boils

- Applying **HT-PEFC** : Large ΔT
- Considering **oil cooling** : Non-boiling coolant

Considering competitive HT-PEFC w/target radiator size, oil cooling

Outline

(1) Simulation results of conventional system

☞ Necessity of HT-PEFC

(2) Construction of oil cooling system

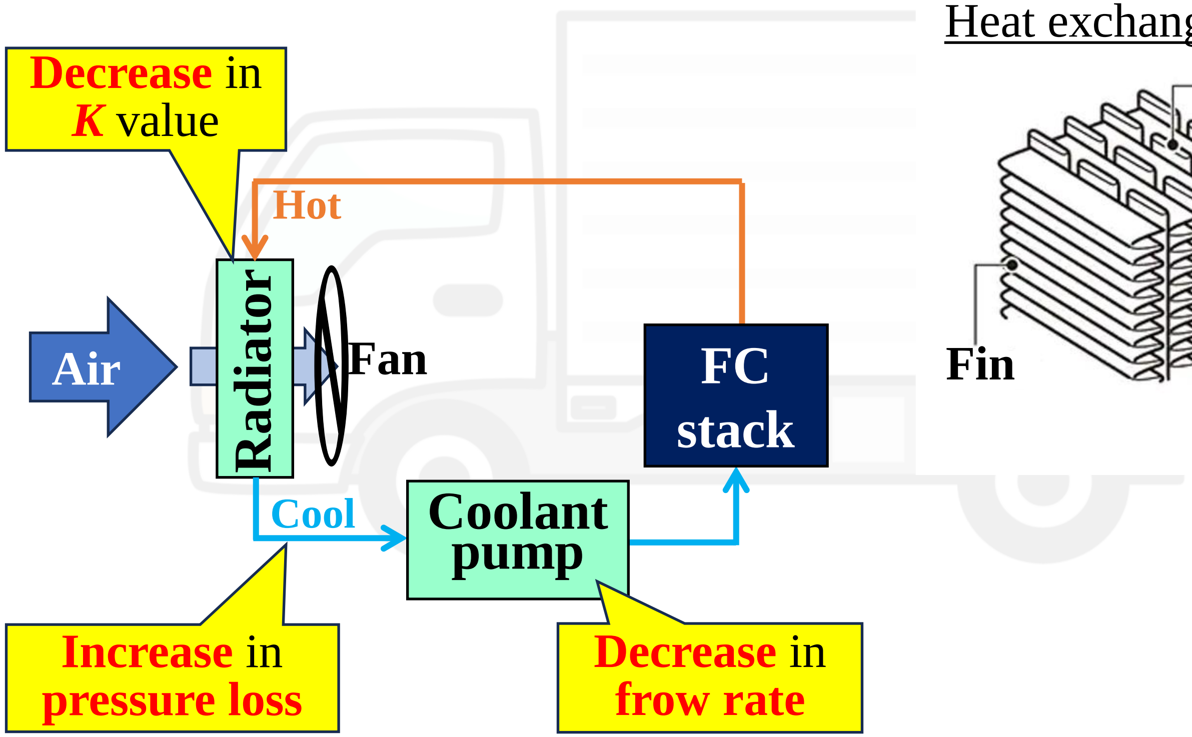
(3) HT-PEFC's IV performance and simulation results

Overview of cooling system

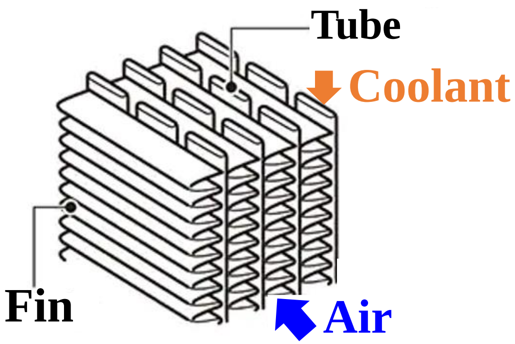
Cooling capacity [W] $Q_{cool} = A \cdot K \cdot \Delta T$

- A : Radiator size [m^2]
- K : **Overall heat transfer coefficient** [W/(m^2・K)]
- ΔT : $T_{FC} - T_{amb.}$ [K]

■ Effect of applying **heat transfer oil** on cooling system



Heat exchange in radiator



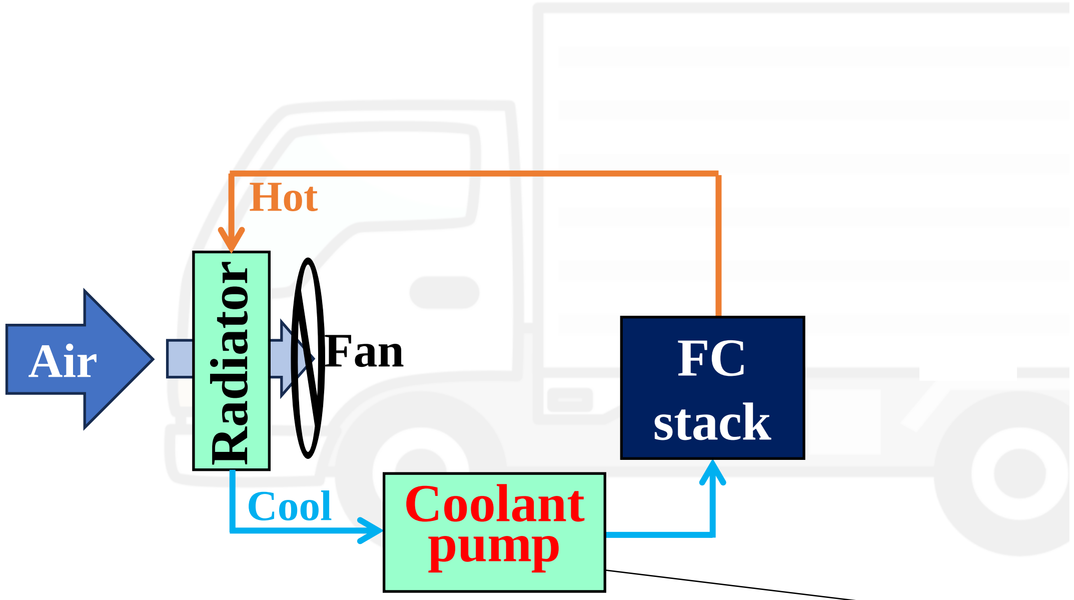
Quantifying the effect of applying oil on cooling capacity is needed

Effect on coolant flow rate

Cooling capacity [W] $Q_{cool} = A \cdot K \cdot \Delta T$

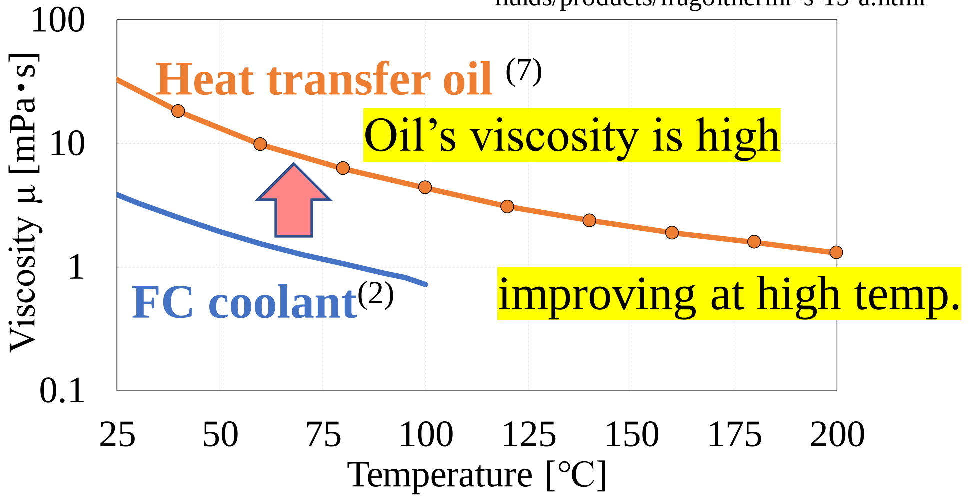
- A : Radiator size [m^2]
- K : **Overall heat transfer coefficient** [$W/(m^2 \cdot K)$]
- ΔT : $T_{FC} - T_{amb.}$ [K]

■ Effect of applying **heat transfer oil** on cooling system



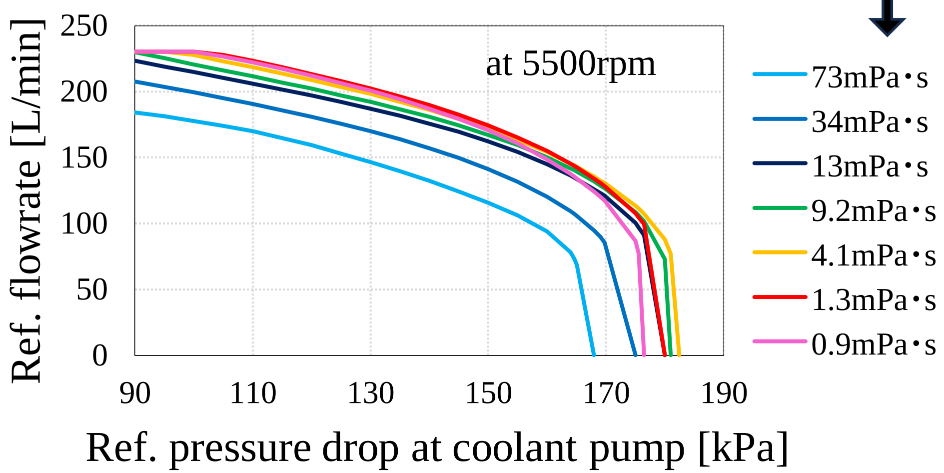
■ Viscosity of coolant

(2) S. Hasegawa et al., *ECS Transactions*, 109, 15-70 (2022).
(7) https://www.fragol.de/en/heat-transfer-fluids/heat-transfer-fluids/products/fragolthermr-s-15-a.html



■ Flow rate by coolant pump

- Considering the influence of **coolant viscosity**
  → **Improved** MIRAI's empirical model [2] is used



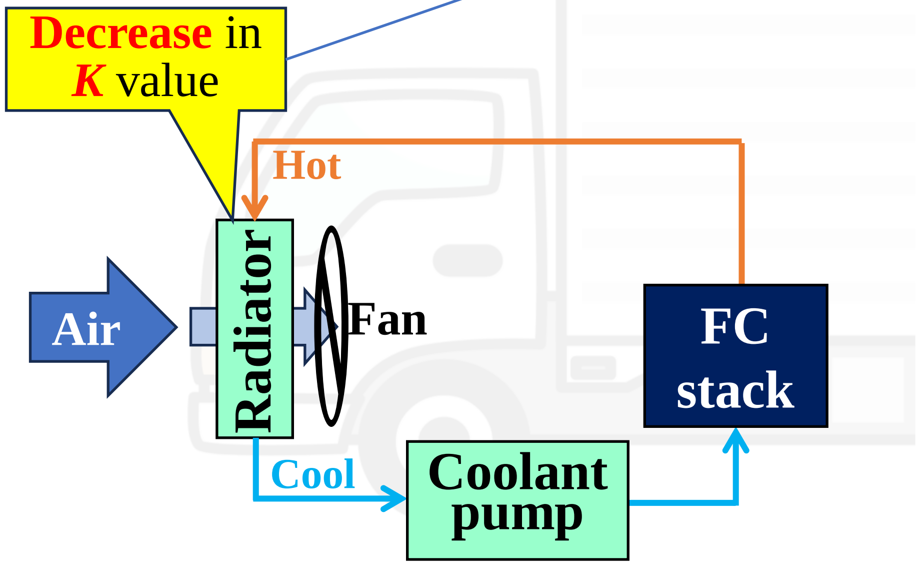
Coolant frow rate model is improved considering viscosity

Effect on K value

Cooling capacity [W] $Q_{cool} = A \cdot K \cdot \Delta T$

- A : Radiator size [m^2]
- K : **Overall heat transfer coefficient** [W/(m^2·K)]
- ΔT : $T_{FC} - T_{amb.}$ [K]

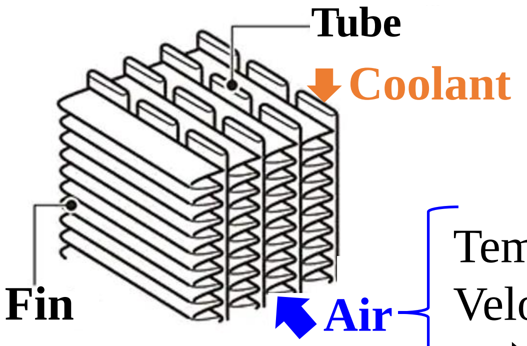
■ Effect of applying **heat transfer oil** on cooling system



■ Formula of K value

$$\frac{1}{A \cdot K} = \underbrace{\frac{1}{\alpha_c \frac{A_c}{A_t + A_f}}}_{\text{Coolant heat transfer}} + \underbrace{\frac{t_t}{\lambda_t \frac{A_c}{A_t + A_f}}}_{\text{Metal thermal conductivity}} + \underbrace{\frac{1}{\alpha_a \eta_a}}_{\text{Air heat transfer}}$$

- α_c : **Coolant**'s heat transfer coefficient (**FCC**→**Oil**)
- α_a : **Air**'s heat transfer coefficient
- η_a : Fin efficiency.
- A : Radiator size
- A_f : Fin's total contact area at air side
- A_t : Tube's total contact area at air side
- A_c : Tube's total contact area at coolant side
- λ_t : Tube's thermal conductivity
- t_t : Tube's thickness



Coolant:
- Temp. : 60～200°C
- Flow rate : 0～240L/min
- ➡ Calculating α_c (FCC→ Oil)

Air:
- Temp. : 30°C
- Velocity : 2～12m/s
- ➡ Calculating α_a

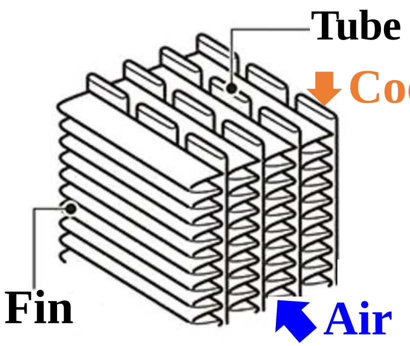
Calculating a value is essential for K value

Effect on *K* value

■ Formula of *K* value

$$\frac{1}{A \cdot K} = \frac{1}{\alpha_c \frac{A_c}{A_t + A_f}} + \frac{t_t}{\lambda_t \frac{A_c}{A_t + A_f}} + \frac{1}{\alpha_a \eta_a}$$

Coolant heat transfer | Metal thermal conductivity | Air heat transfer

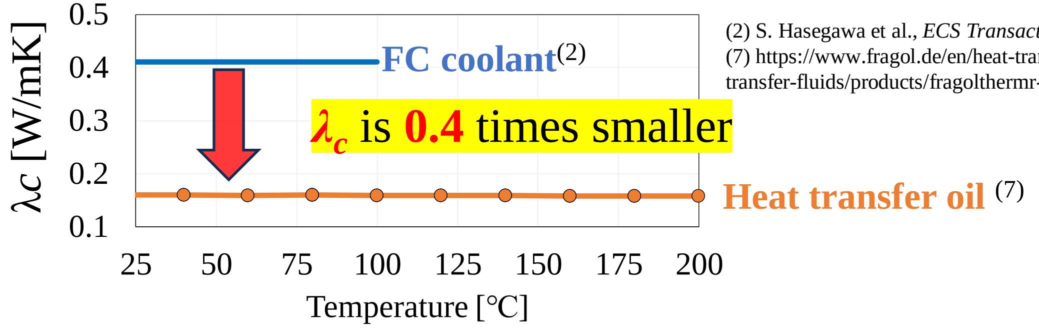


Temp. : 60～200℃
Flow rate : 0～240L/min
➡ Calculating α_c (FCC→ Oil)

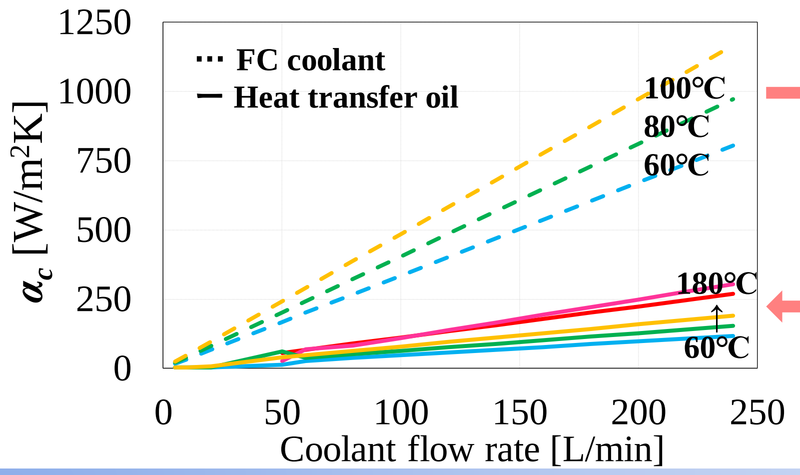
$$\alpha_c = \frac{Nu \cdot \lambda_c}{L}$$

α_c : Coolant's **heat transfer coefficient**
N_u : **Nusselt number**
λ : **Thermal conductivity**
L : Effective length

Boundary condition	Nusselt number : *Nu* (Gnielinski Eqs.)	Friction coefficient : *f* (Haaland Eqs.)
$Re < 2000$	$Nu = 3.66$	$f = \frac{64}{Re}$
$2000 \le Re < 4000$	$Nu = \left(\frac{Re-2000}{2000}\right)\left[\frac{\left(\frac{f}{8}\right) Re\, Pr}{1+12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)} - 3.66\right] + 3.66$	$f = \left(\frac{Re-2000}{2000}\right)\frac{1}{\left[-1.8\log_{10}\left\{\left(\frac{\varepsilon}{3.7d}\right)^{1.11}+\frac{6.9}{Re}\right\}\right]^2} + \left(1-\frac{Re-2000}{2000}\right)\frac{64}{Re}$
$Re \ge 4000$	$Nu = \frac{\left(\frac{f}{8}\right) Re\, Pr}{1+12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)}$	$f = \frac{1}{\left[-1.8\log_{10}\left\{\left(\frac{\varepsilon}{3.7d}\right)^{1.11}+\frac{6.9}{Re}\right\}\right]^2}$



(2) S. Hasegawa et al., *ECS Transactions*, 109, 15-70 (2022).
(7) https://www.fragol.de/en/heat-transfer-fluids/heat-transfer-fluids/products/fragolthermr-s-15-a.html



Compared to FCC, oil's α_c is reduced to 0.2 times

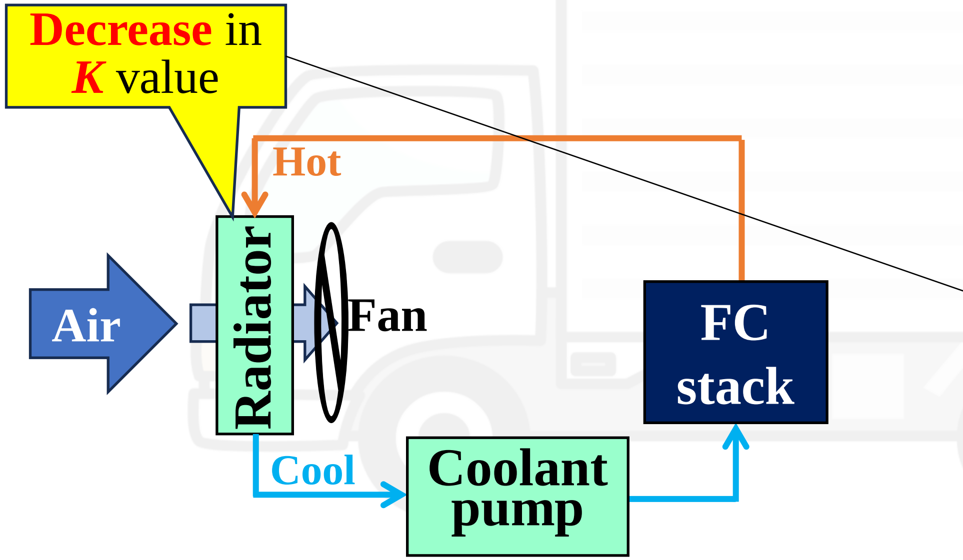
By using oil, α_c is reduced to 1/5 → Estimating *K* value

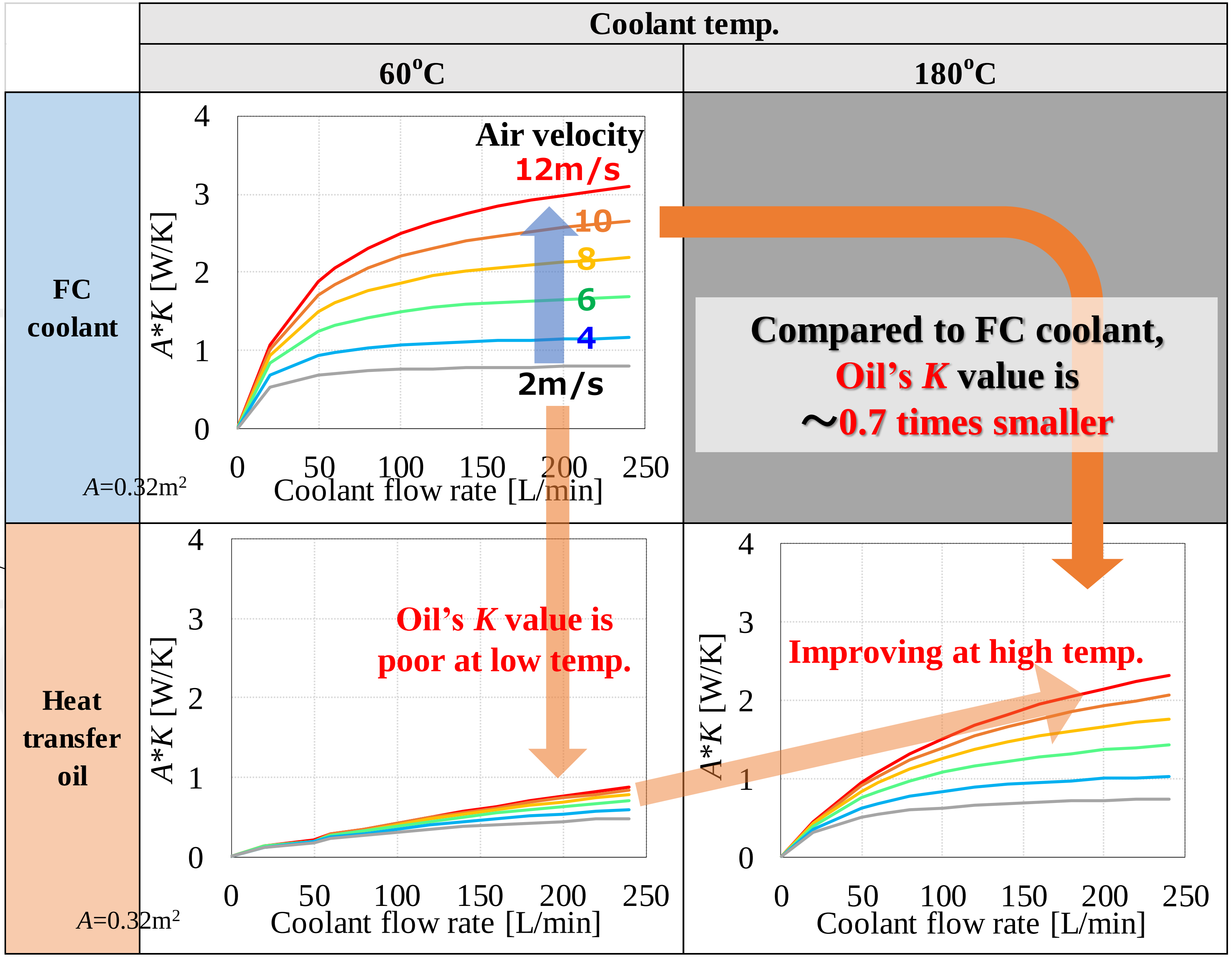
Estimating result of *K* value from formula

Cooling capacity [W] $Q_{cool} = A \cdot K \cdot \Delta T$

- A : Radiator size [m^2]
- K : **Overall heat transfer coefficient** [$W/(m^2 \cdot K)$]
- ΔT : $T_{FC} - T_{amb.}$ [K]

■ Effect of applying **heat transfer oil** on cooling system





***K* value is improved at high temp.→ Oil cooling could be used for HT-PEFC**

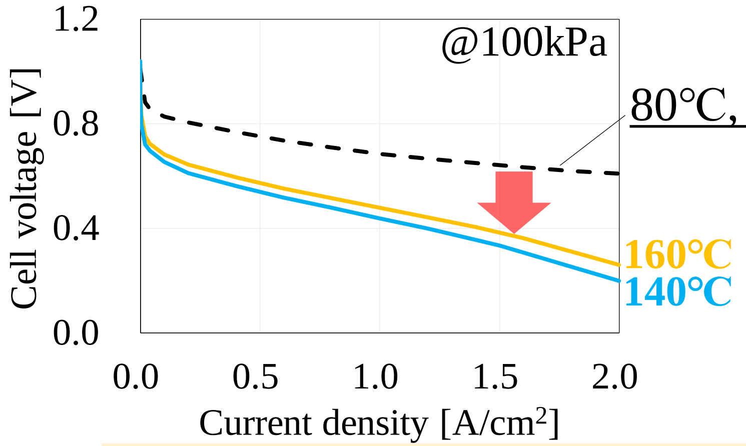
(1) Simulation results of conventional system

☞ Necessity of HT-PEFC

(2) Construction of oil cooling system

(3) HT-PEFC's IV performance and simulation results

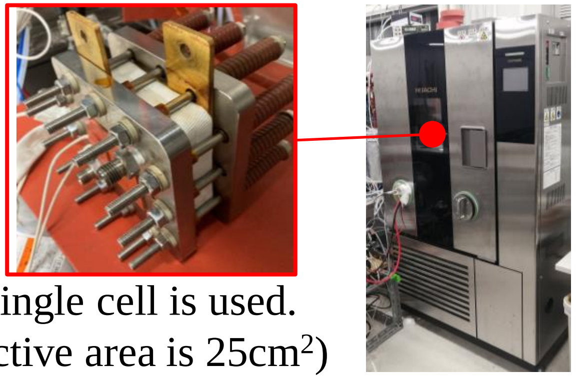
IV characteristics of MIRAI-MEA & PBI-MEA



80℃, MIRAI-MEA
calculated by FC-DynaMo[1,2,3]

PBI-MEA
obtained by experiments

(1) S. Hasegawa et al., *ECS Transactions*, 104, 3-26 (2021).
(2) S. Hasegawa et al., *ECS Transactions*, 109, 15-70 (2022).
(3) S. Hasegawa et al., *Comput. Aided Chem. Eng*, 49, 1123-1128 (2022).

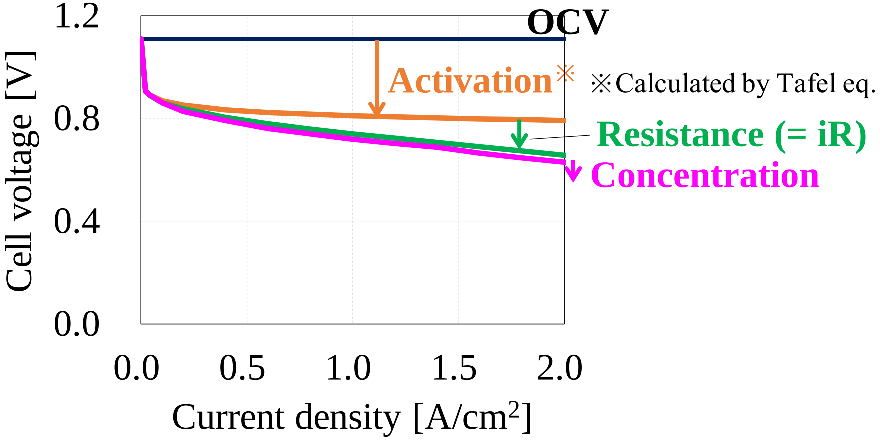


Single cell is used.
(Active area is 25cm²)

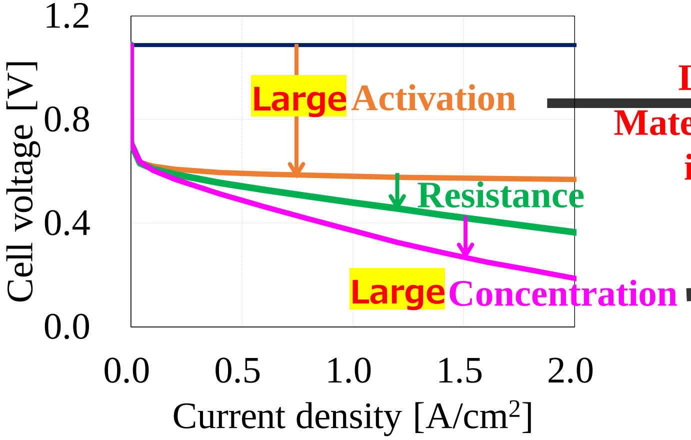
Compared to MIRAI-MEA,
PBI-MEA's overpotential is very large.

■Separation of overpotential

MIRAI-MEA@80℃, 100kPa



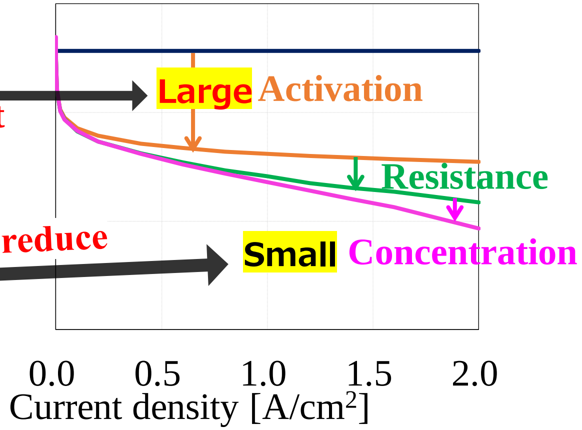
PBI-MEA@160℃, 100kPa



Limit to reduce
Material improvement is also required

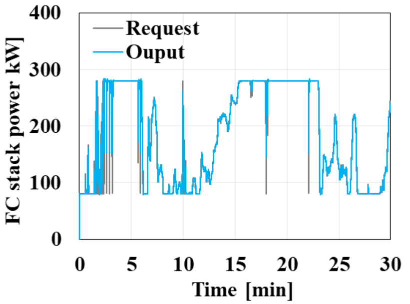
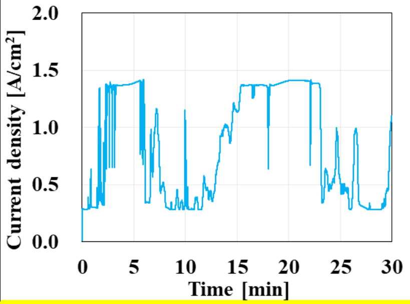
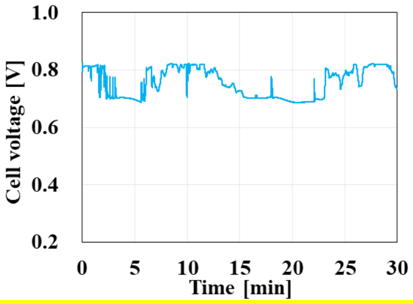
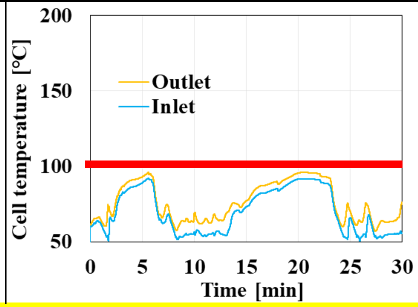
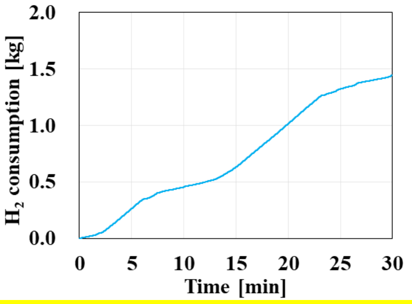
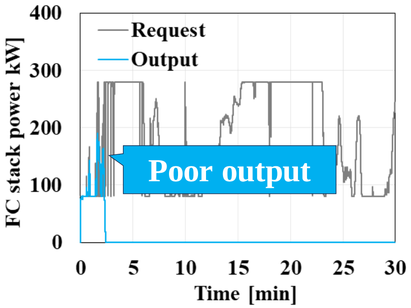
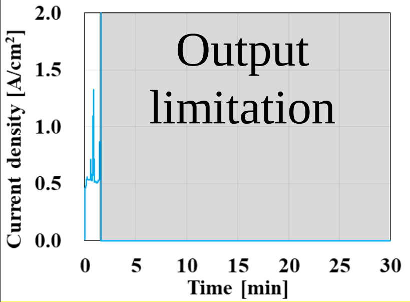
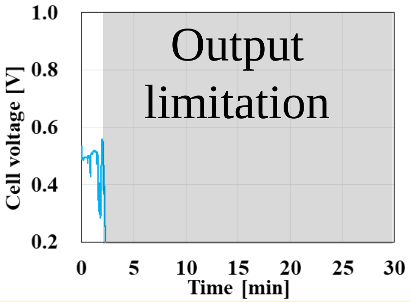
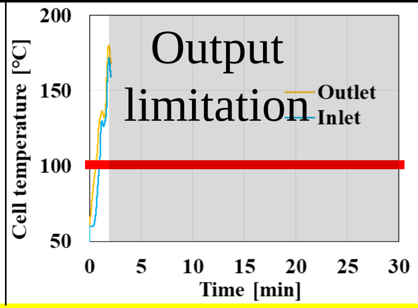
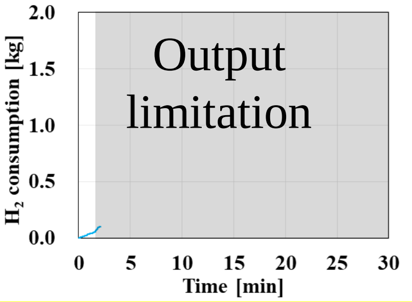
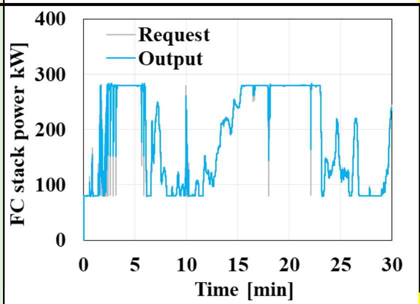
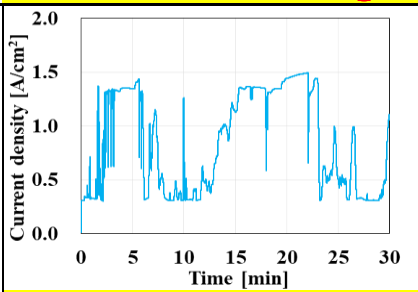
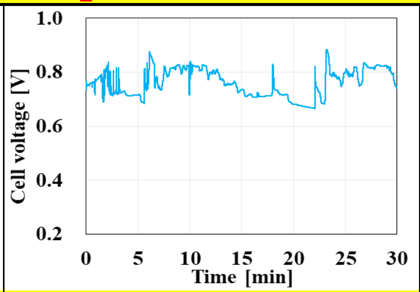
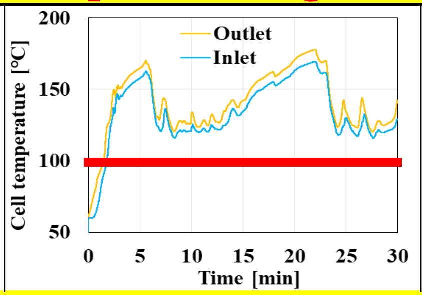
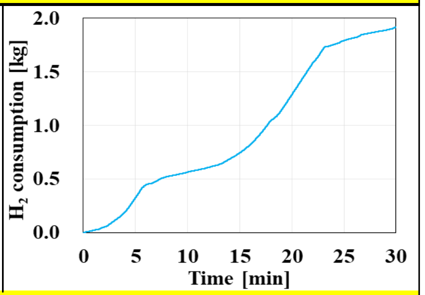
Possible to reduce

PBI-MEA@160℃, 250kPa



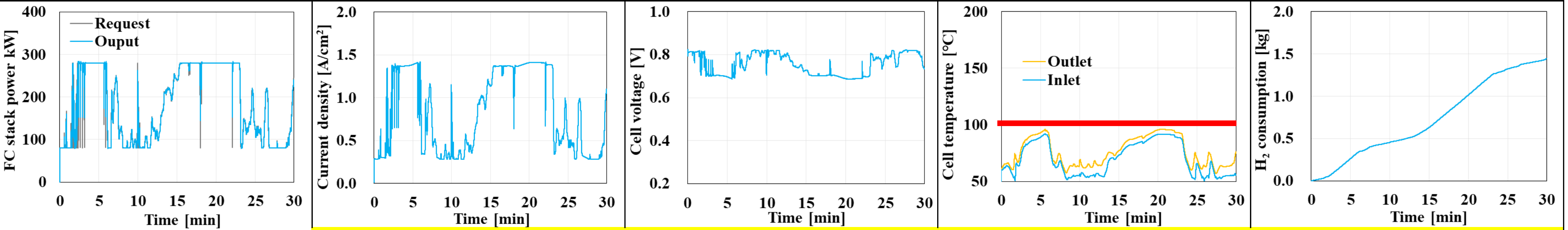
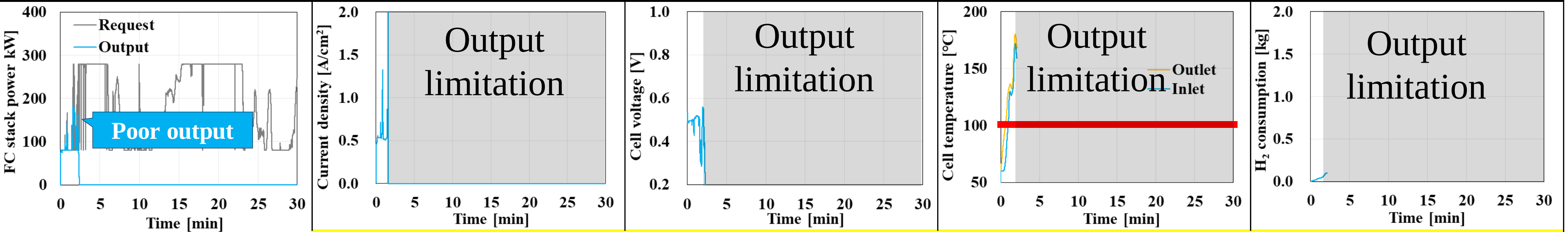
PBI has large activation overpotential → Proposing required performance

HDV driving simulation results by FC-DynaMo

MEA	Coolant	Radiator size	FC stack net power	Current density	Cell voltage	Cell temp.	H_2 consumption
MIRAI	Conv. FC coolant	1.28m^2 (Ref.)					
				Possible to drive **below 100°C**			
PBI	Thermal transfer oil (S15A)	0.83m^2 (Target)					
				Large overpotential → **Poor output** and **large waste heat**			
Virtual HT-MEA	↑	↑					
				Given required_IV performance → Possible to drive at **high-temp.**			

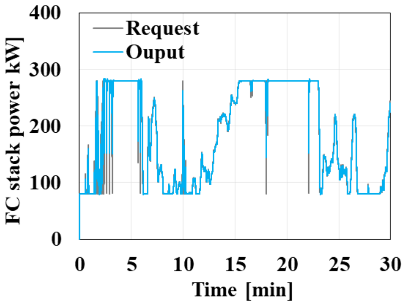
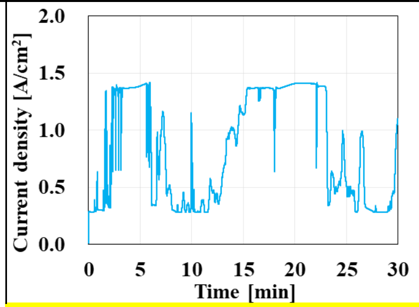
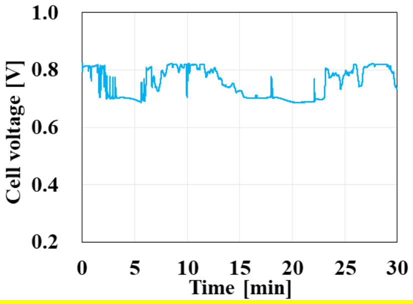
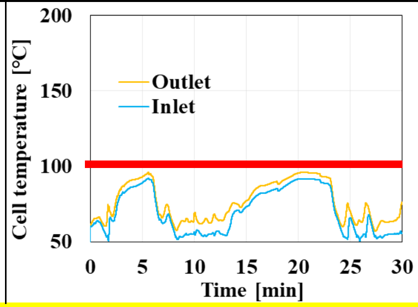
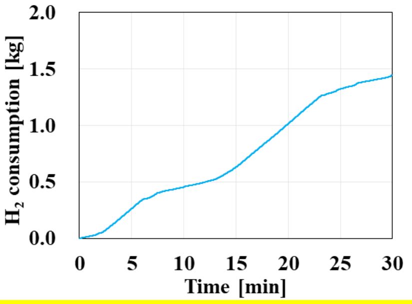
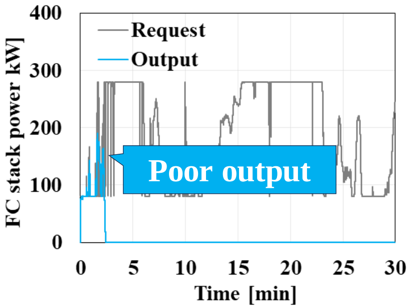
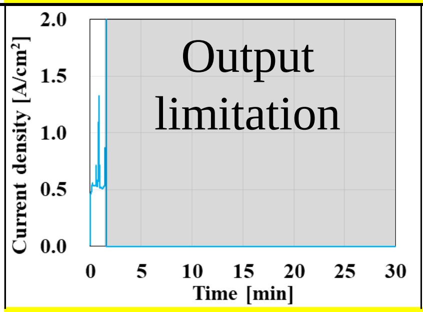
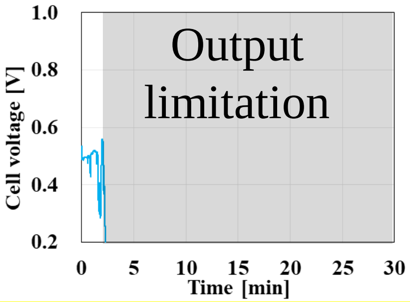
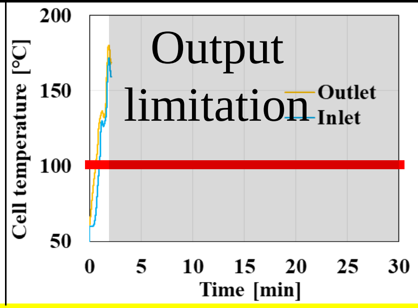
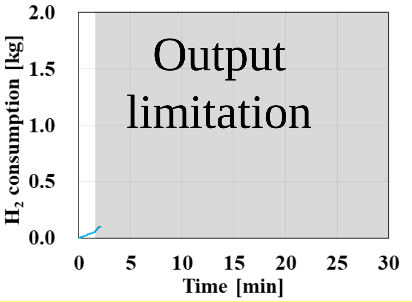
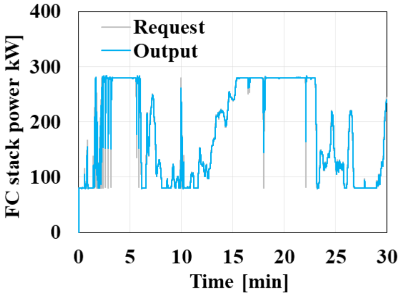
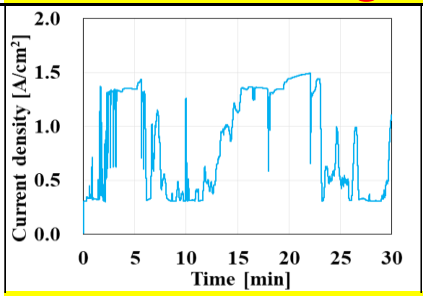
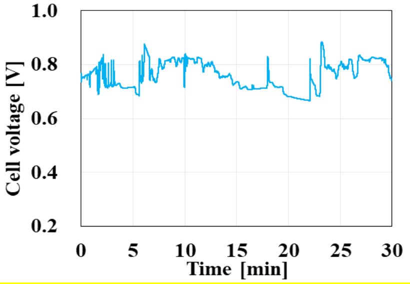
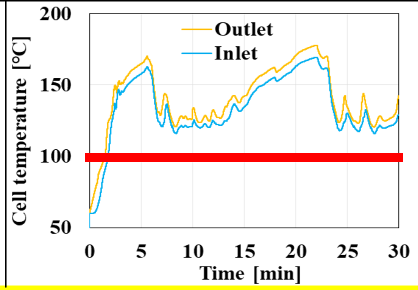
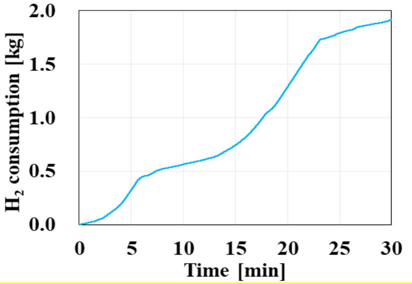
Virtual HT-MEA x oil cooling : Possible to operate w/small radiator

HDV driving simulation results by FC-DynaMo

MEA	Coolant	Radiator size	FC stack net power	Current density	Cell voltage	Cell temp.	H_2 consumption
MIRAI	Conv. FC coolant	1.28m^2 (Ref.)					
				Possible to drive **below 100°C**			
PBI	Thermal transfer oil (S15A)	0.83m^2 (Target)					
				Large overpotential → **Poor output** and **large waste heat**			
Virtual HT-MEA	↑	↑					
				Given necessary IV performance → Possible to drive at **high-temp.**			

Impossible to operate w/PBI-MEA's because of large overpotential

HDV driving simulation results by FC-DynaMo

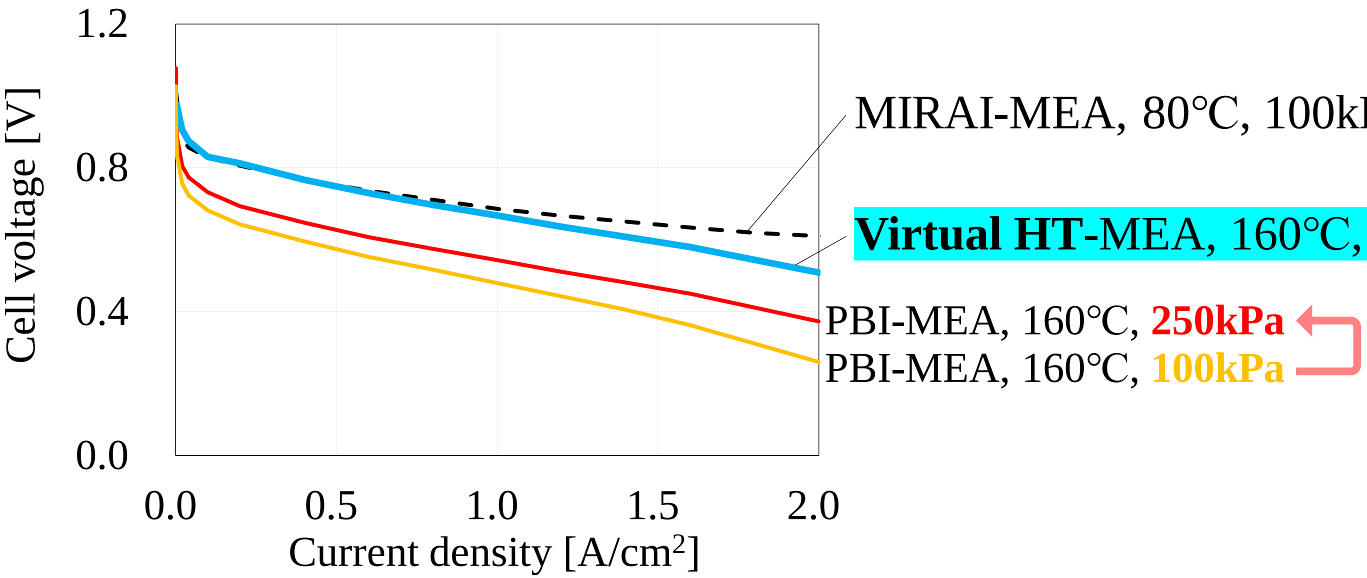
MEA	Coolant	Radiator size	FC stack net power	Current density	Cell voltage	Cell temp.	H_2 consumption
MIRAI	Conv. FC coolant	1.28m^2 (Ref.)					
				Possible to drive **below 100°C**			
PBI	Thermal transfer oil (S15A)	0.83m^2 (Target)					
				Large overpotential → **Poor output** and **large waste heat**			
Virtual HT-MEA	↑	↑					
				Given required_IV performance → Possible to drive at **high-temp.**			

Given required IV performance

Oil cooling's disadvantage ≪ Large ΔT

Virtual HT-MEA x oil cooling : Possible to operate w/small radiator

Required IV performance for competitive HT-PEFC

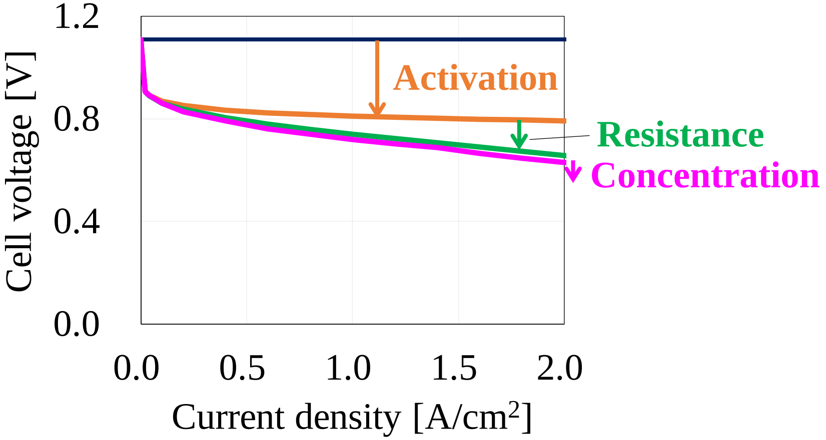


- Required performance for HT-PEFC
- Target for material improvement

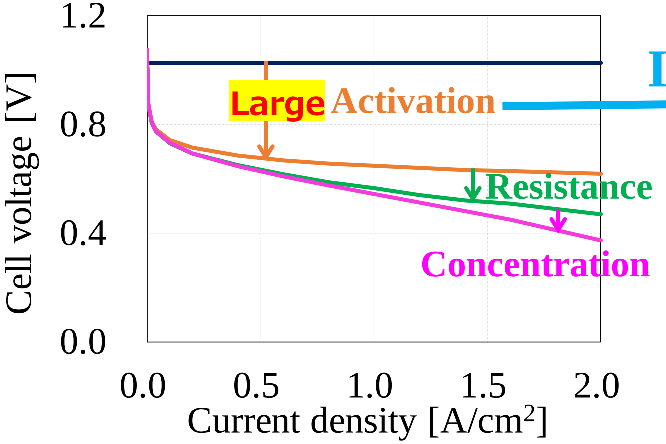
Possible to reduce concentration overpotential

■Separation of overpotential

MIRAI-MEA@80°C, 100kPa

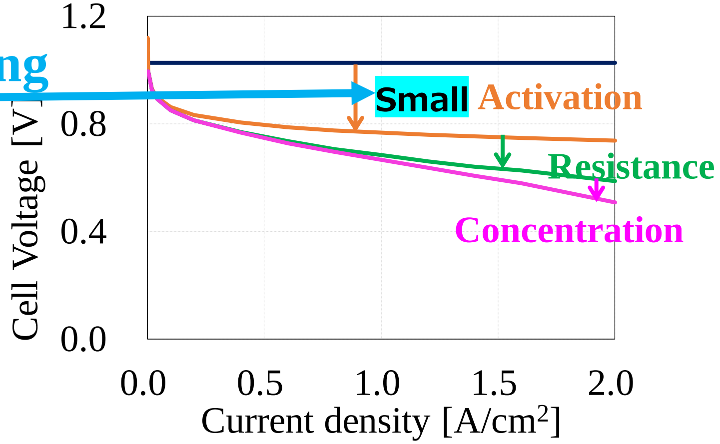


PBI-MEA@160°C, 250kPa



Improving

Virtual HT-MEA@160°C, 250kPa



Improving activation overpotential to the same level as MIRAI is required

Conclusion

■We evaluated HT-PEFC's utility for HDV by FC system simulator.

- By applying oil cooling, the cooling capacity is very poor at low temp. However, the cooling capacity is improved at high temp.
  Oil cooling is effective for HT-PEFC.

- HT-PEFC has large concentration overpotential because the oxygen molar concentration decreases at high temp., but this can be improved by increasing the gas pressure.

- Current HT-PEFC (e.g. PBI) has large activation overpotential, resulting in insufficient output and large waste heat.

- By improving the activation overpotential to the same level as MIRAI, HDV is possible to drive with oil cooling system and small radiator size.

Acknowledgment

- We would like to thank Prof. Hasegawa and Prof. Kawase of Kyoto University and the development staff for their great support in using FC-DynaMo.

- This study was supported by the ***SUZUKI FOUNDATION***, Japan.