# Experimental Study and Numerical Interpretation on the Temperature Field of DPF during Active Regeneration with Hydrocarbon Injection

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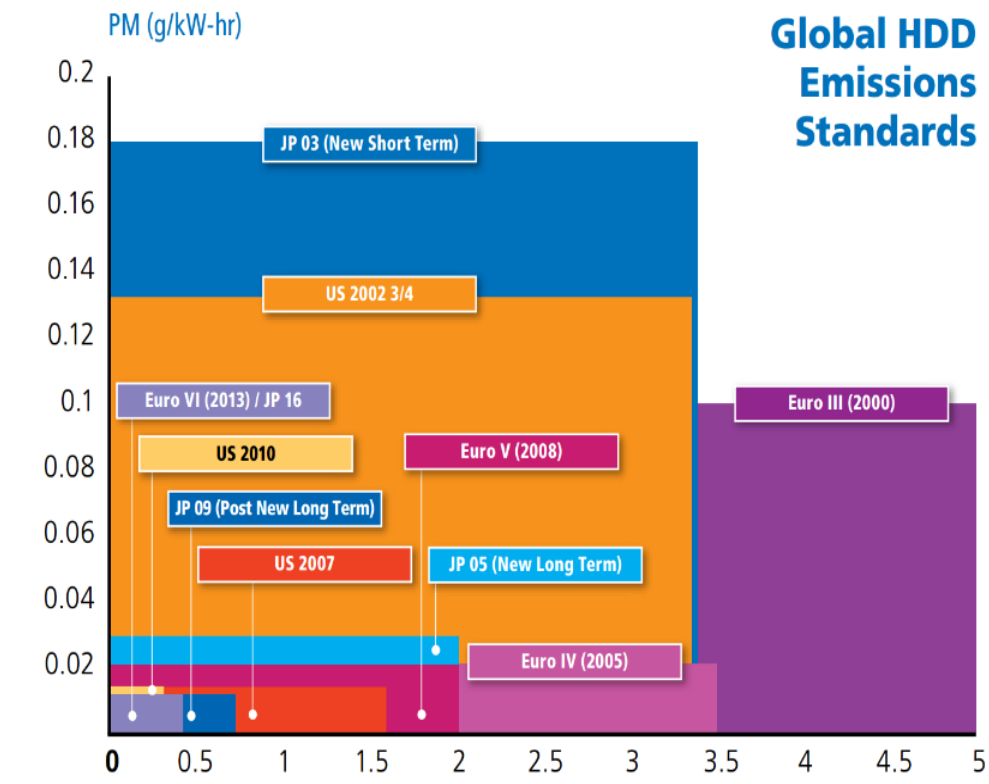
# Outline

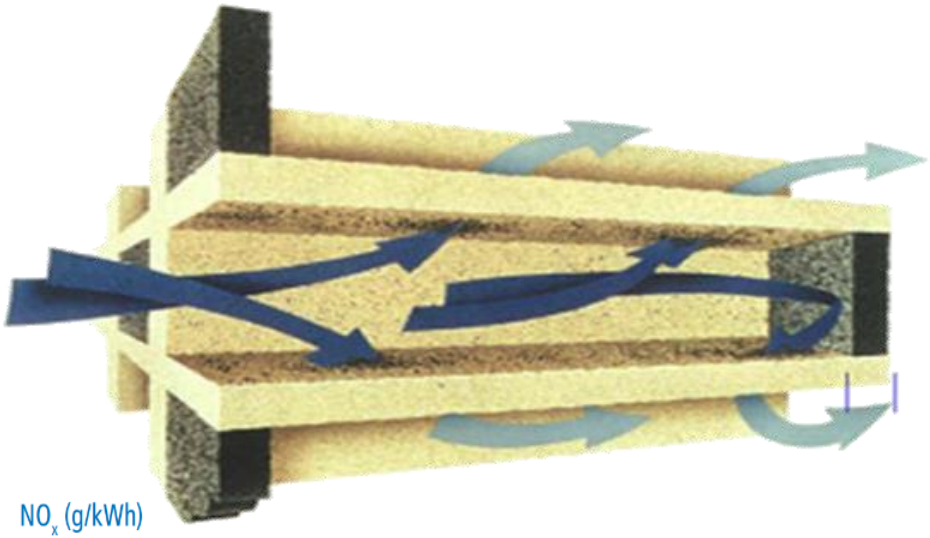
- Introduction
- Experimental Study
- Numerical Interpretation (CFD Modeling)
- Summary
- Acknowledgements

# Introduction

- Diesel particulate filter (DPF) is indispensable for diesel engines to meet the increasingly stringent emission regulations.
- Regeneration is needed for the DPF to burn off the accumulated soot in the DPF.

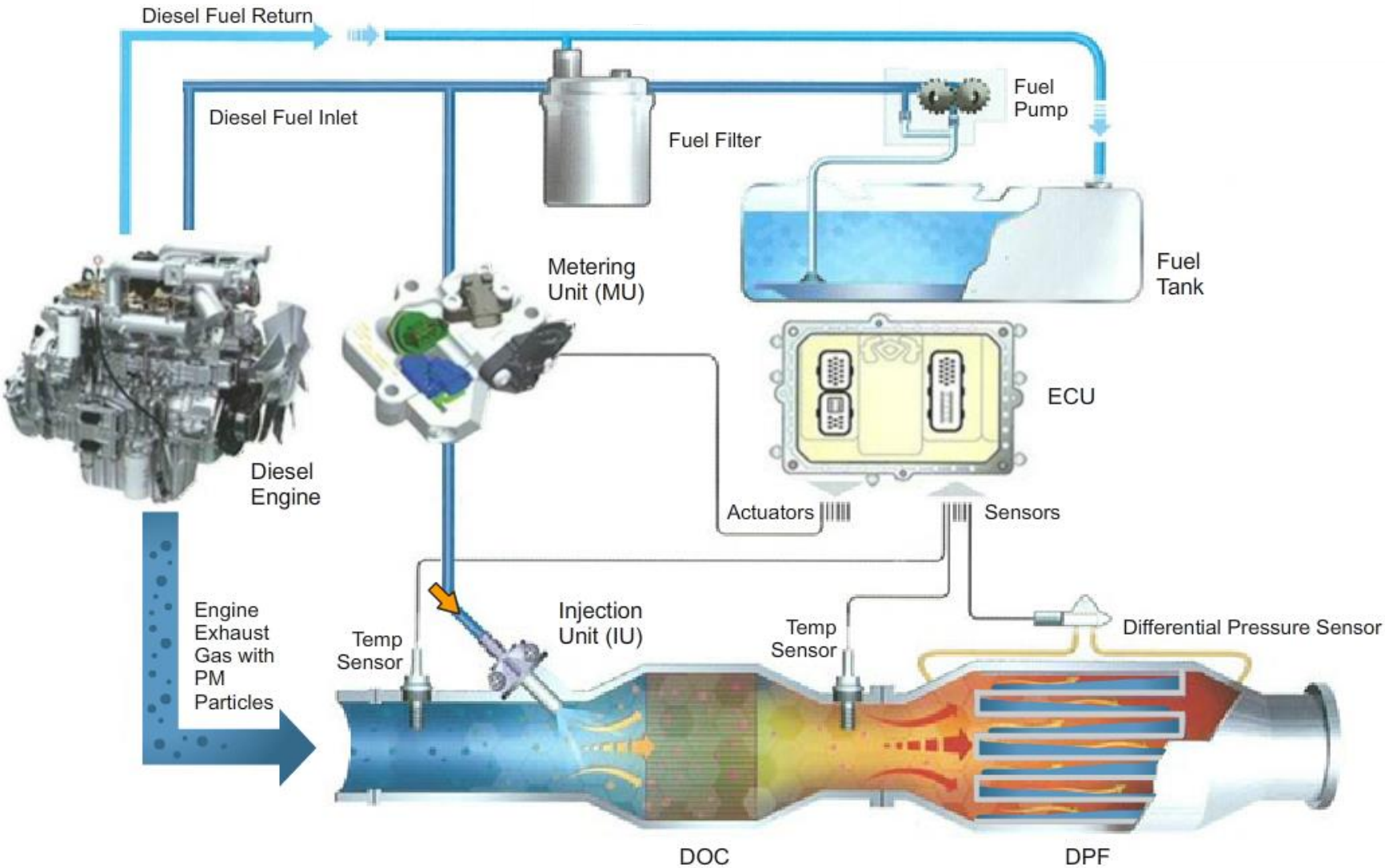






# Introduction

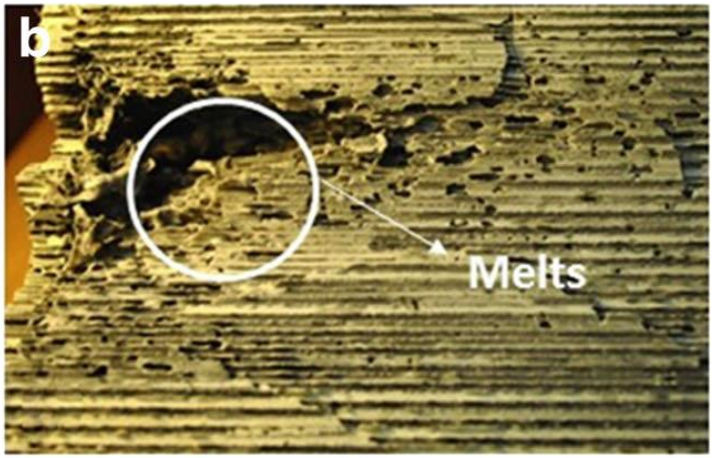
- The active regeneration process of the DPF.



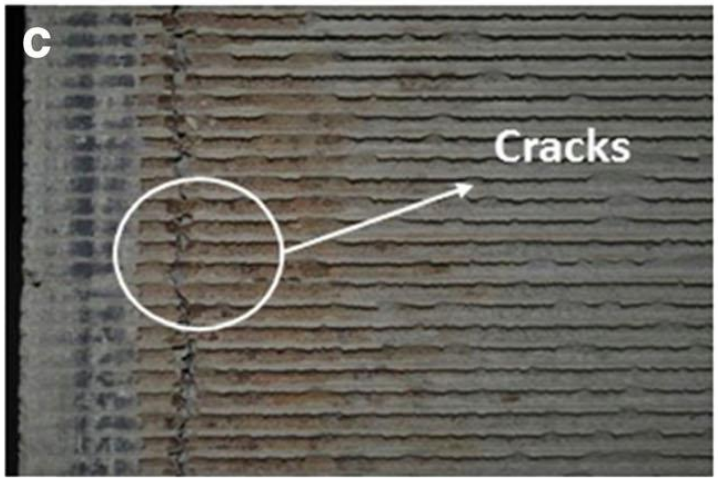
# Introduction

- Both the peak temperature and the maximum temperature gradient of the DPF during active regeneration should be well controlled in order to enhance the reliability and durability of the filter.

Too high temperature
(>1100℃ for cordierite DPF)




Too high temperature gradient
(>350℃/cm for cordierite DPF)



# Experiment Setup

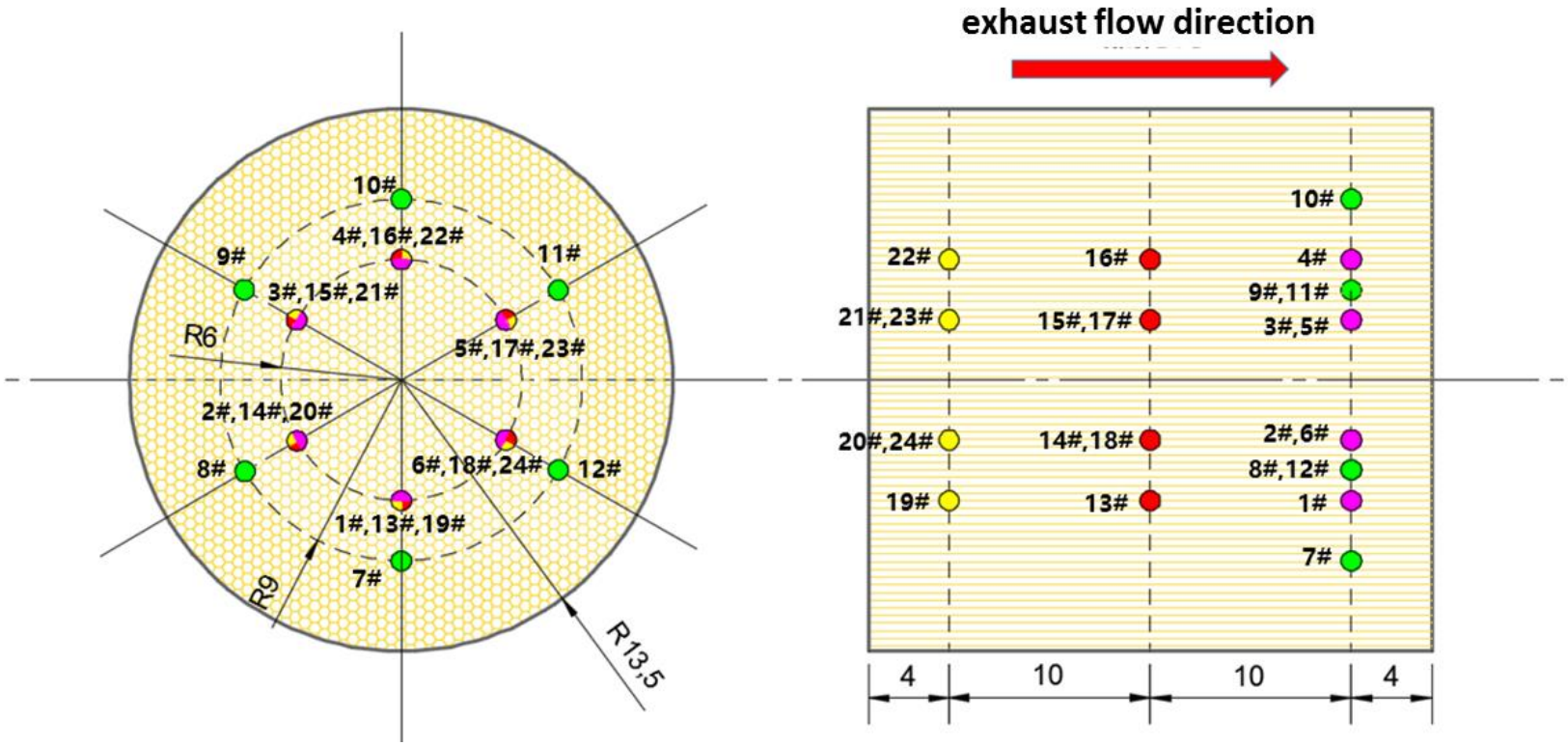
## Engine and catalysts specifications

| | |
|---|---|
| Engine type | Diesel, 4-strokes, 6-cylinders in line |
| Air intake system | Inter-cooled, turbocharged |
| Fuel metering system | High pressure common rail |
| Bore | 110 mm |
| Stroke | 132 mm |
| Displacement | 7.5 L |
| Compression ratio | 17.4 |
| Rated power | 248 kW @ 2300 rpm |
| Maximum torque | 1350 N·m @ 1200-1700 rpm |


| Catalysts | Specifications |
|---|---|
| DOC | Φ10.5"x6 " |
| | 400 cpsi/4 mil |
| CDPF | Φ10.5"x11 " |
| | 200 cpsi/12 mil |

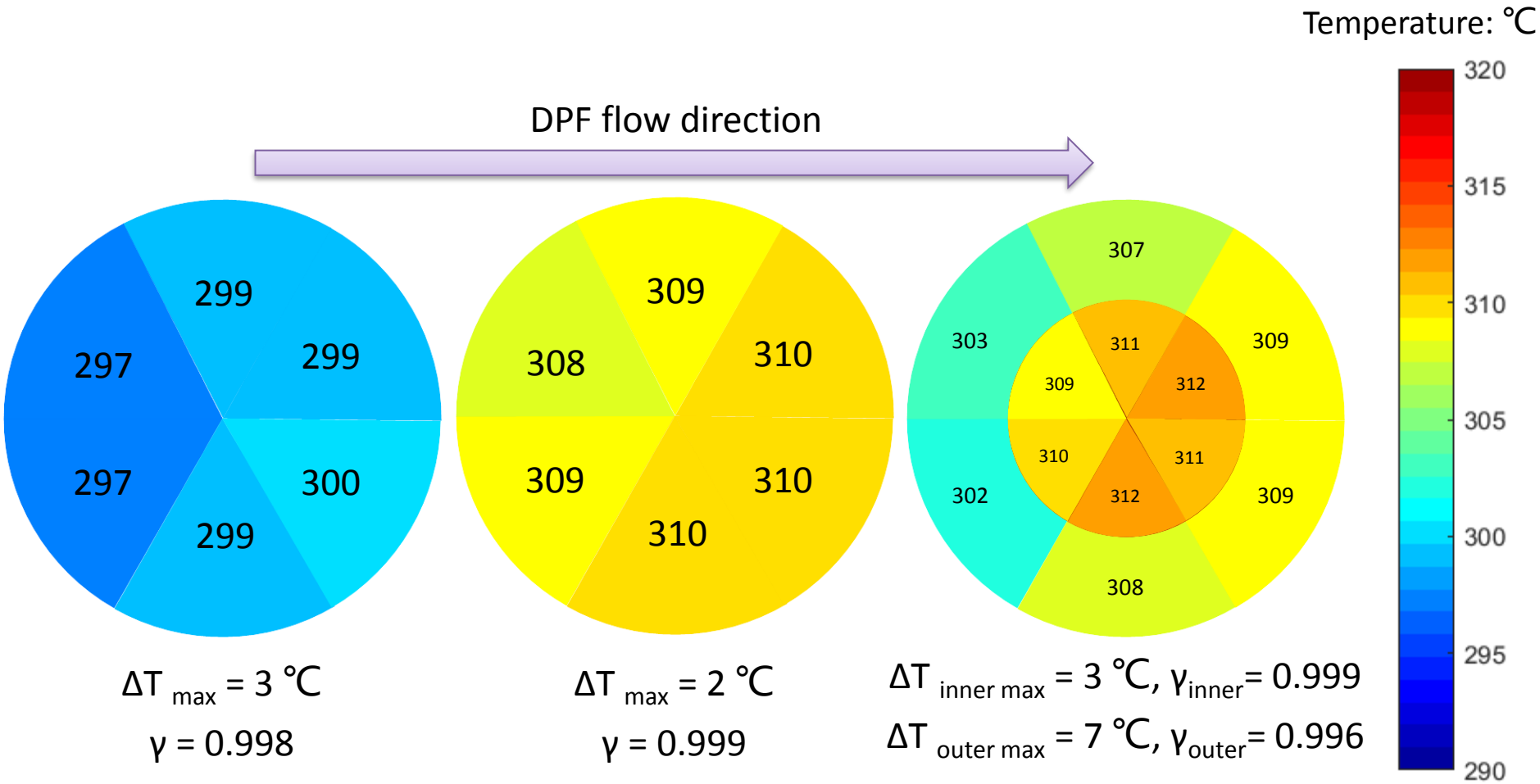
# Circumferential Uniformity Test

- 24 thermocouples were inserted into the DPF channels to measure the inner temperature of the filter.
- The temperature circumferential uniformity of three different sections at the DPF length direction was analyzed.



# Circumferential Uniformity Test

- **Case 1**: no soot loading in DPF, no HC injection.
- The temperature circumferential distribution of the three sections is very homogeneous.




$\Delta T_{max} = 3$ ℃

$\gamma = 0.998$

$\Delta T_{max} = 2$ ℃

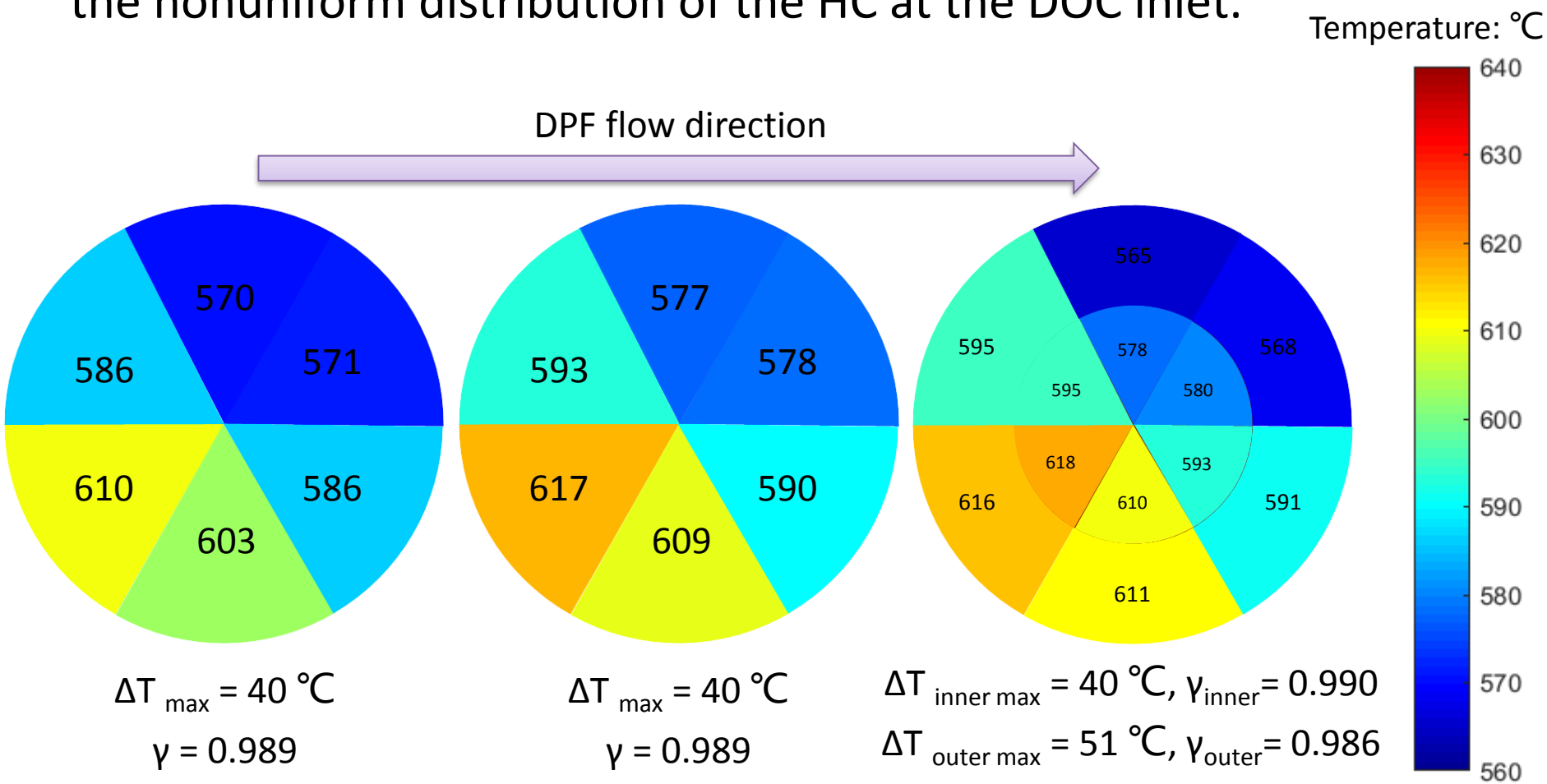
$\gamma = 0.999$

$\Delta T_{inner\ max} = 3$ ℃, $\gamma_{inner} = 0.999$

$\Delta T_{outer\ max} = 7$ ℃, $\gamma_{outer} = 0.996$

# Circumferential Uniformity Test

- **Case 2**: no soot loading in DPF, with HC injection.
- The temperature at the left-bottom region is higher than that of the right-top region in all the three sections, which should be caused by the nonuniform distribution of the HC at the DOC inlet.




$\Delta T_{max}$ = 40 ℃

$\gamma$ = 0.989

$\Delta T_{max}$ = 40 ℃

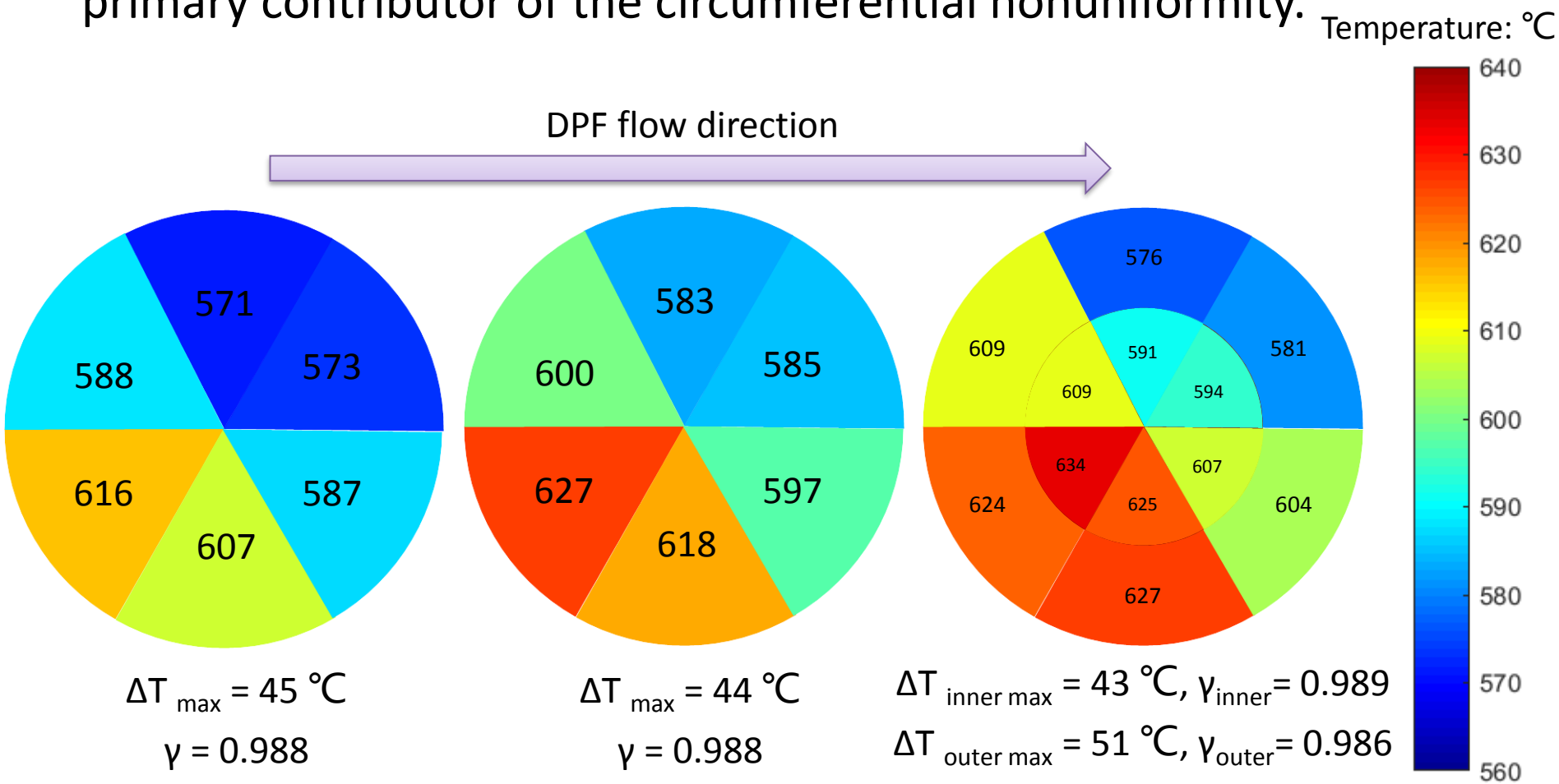
$\gamma$ = 0.989

$\Delta T_{inner\ max}$ = 40 ℃, $\gamma_{inner}$= 0.990

$\Delta T_{outer\ max}$ = 51 ℃, $\gamma_{outer}$= 0.986

# Circumferential Uniformity Test

- **Case 3**: DPF soot loading = 3 g/L, with HC injection.
- The temperature circumferential distribution of the three sections is highly similar with case 2, which indicates that the HC spray is the primary contributor of the circumferential nonuniformity.




$\Delta T_{max}$ = 45 ℃

$\gamma$ = 0.988

$\Delta T_{max}$ = 44 ℃

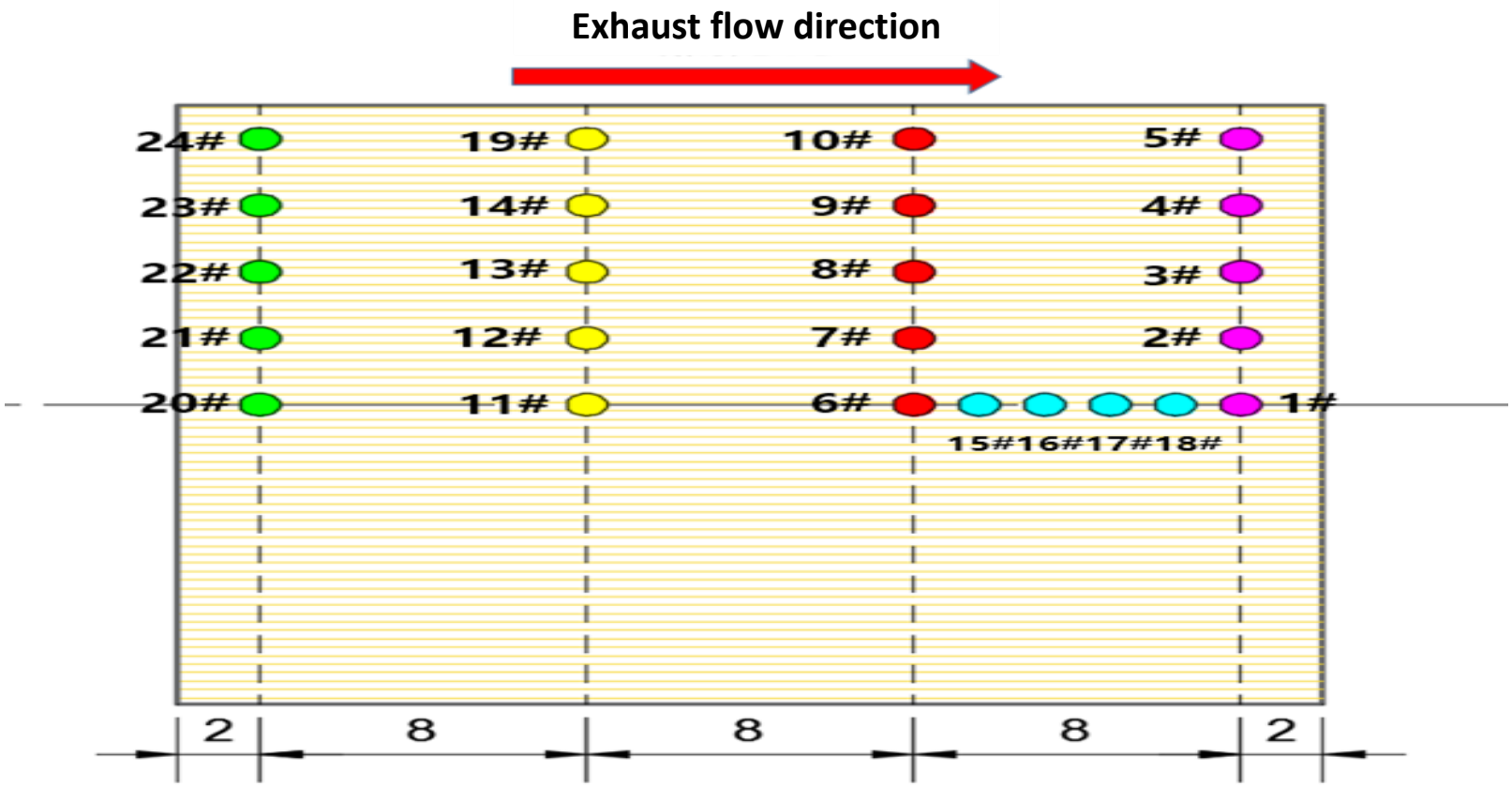
$\gamma$ = 0.988

$\Delta T_{inner\ max}$ = 43 ℃, $\gamma_{inner}$ = 0.989

$\Delta T_{outer\ max}$ = 51 ℃, $\gamma_{outer}$ = 0.986

# Axial and Radial Uniformity Test

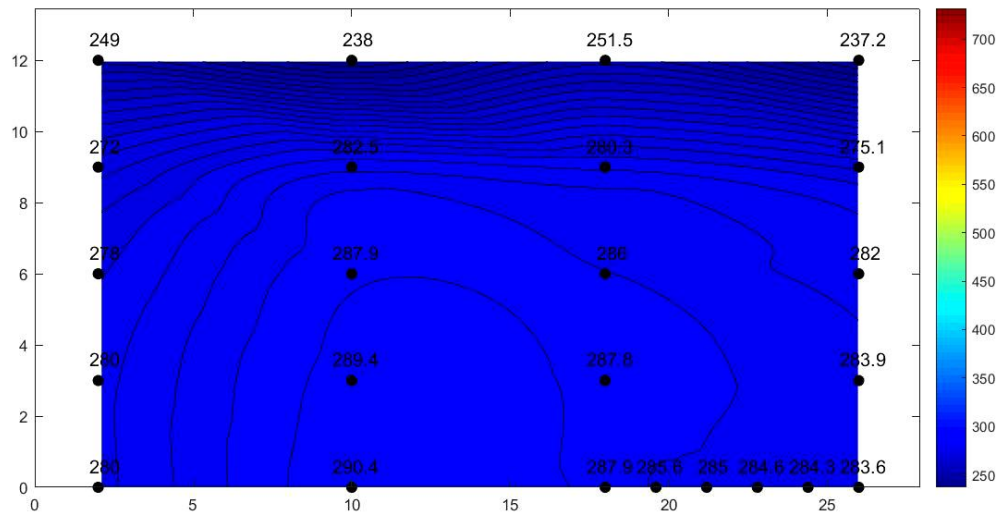
- A new thermocouple layout configuration was adopted to evaluate the axial and radial uniformity of the DPF temperature field during active regeneration.



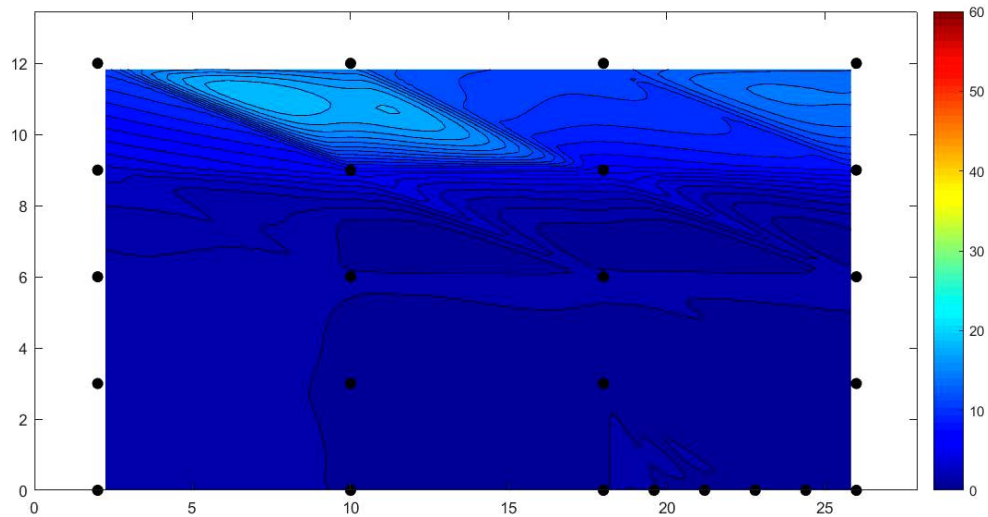
# Axial and Radial Uniformity Test

- The DPF temperature field was visualized using cubic interpolation based on the measured temperature data.

Temperature (℃)




Temperature gradient (℃/cm)



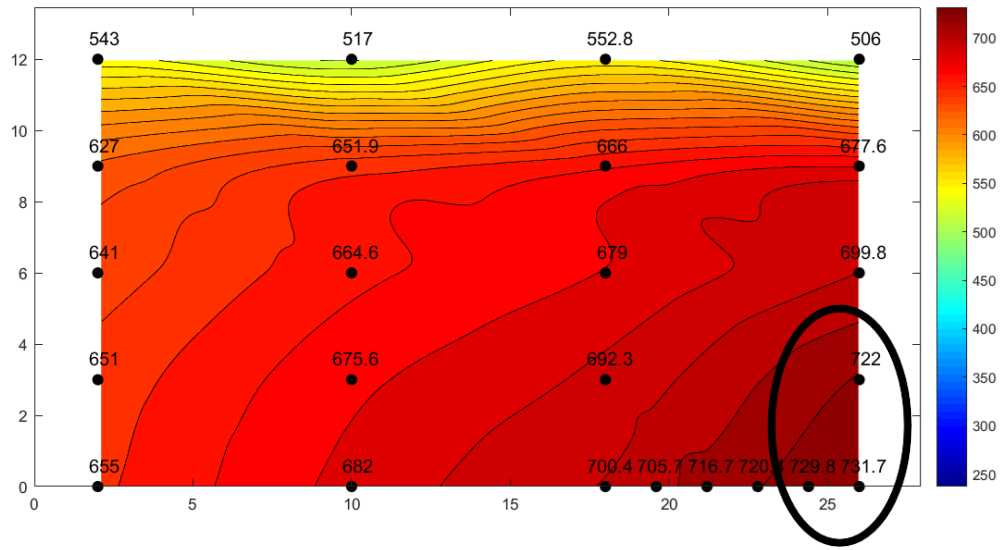

**Regeneration conditions:**
exhaust mass flow = 440 kg/h
DPF soot loading = 4 g/L
DPF inlet temperature = 600 ℃

# Axial and Radial Uniformity Test

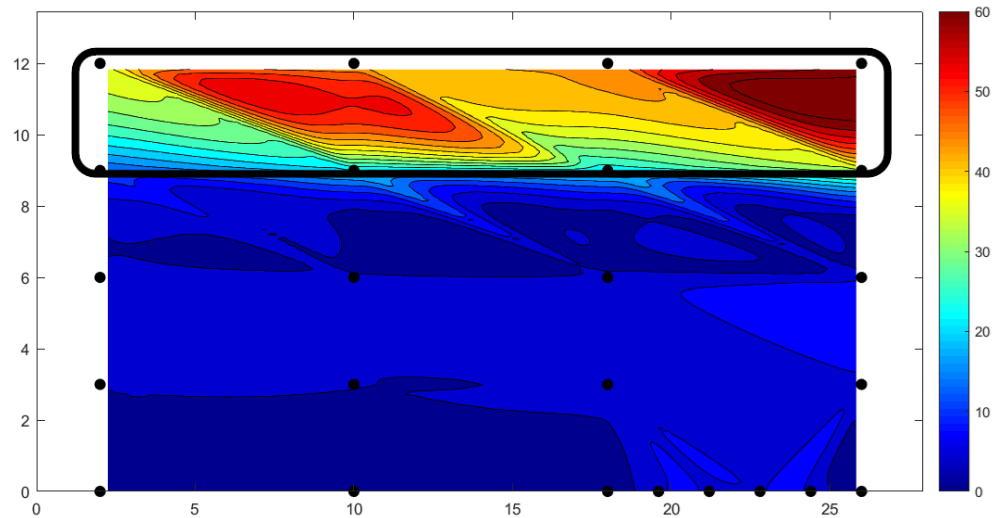
- The DPF temperature field was visualized using cubic interpolation based on the measured temperature data.
- The peak temperature occurred at the center of the DPF rear end.
- The maximum temperature gradient occurred at the DPF outer edge.

**Regeneration conditions:**
exhaust mass flow = 440 kg/h
DPF soot loading = 4 g/L
DPF inlet temperature = 600 ℃

Temperature (℃)

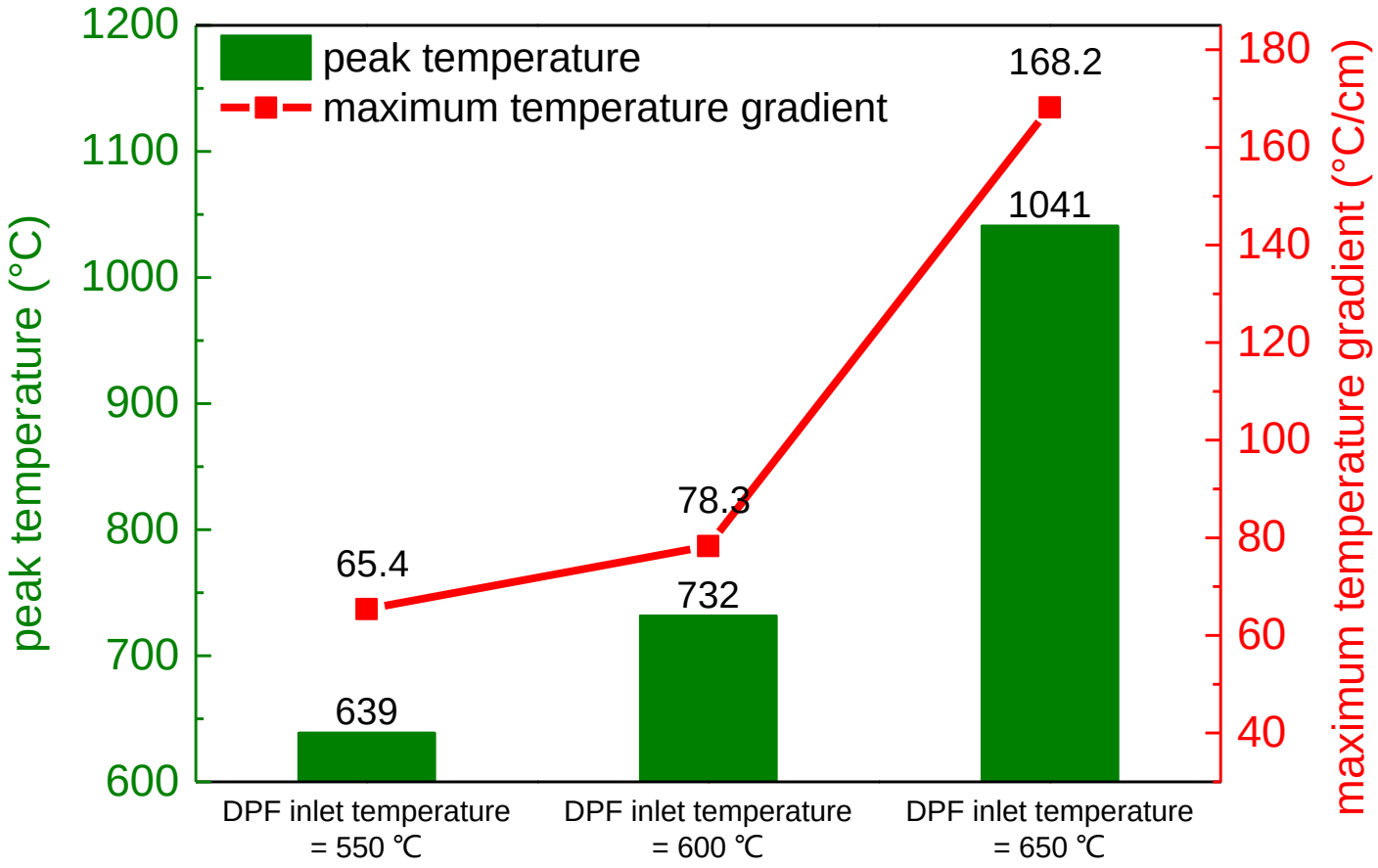



Temperature gradient (℃/cm)



# Axial and Radial Uniformity Test

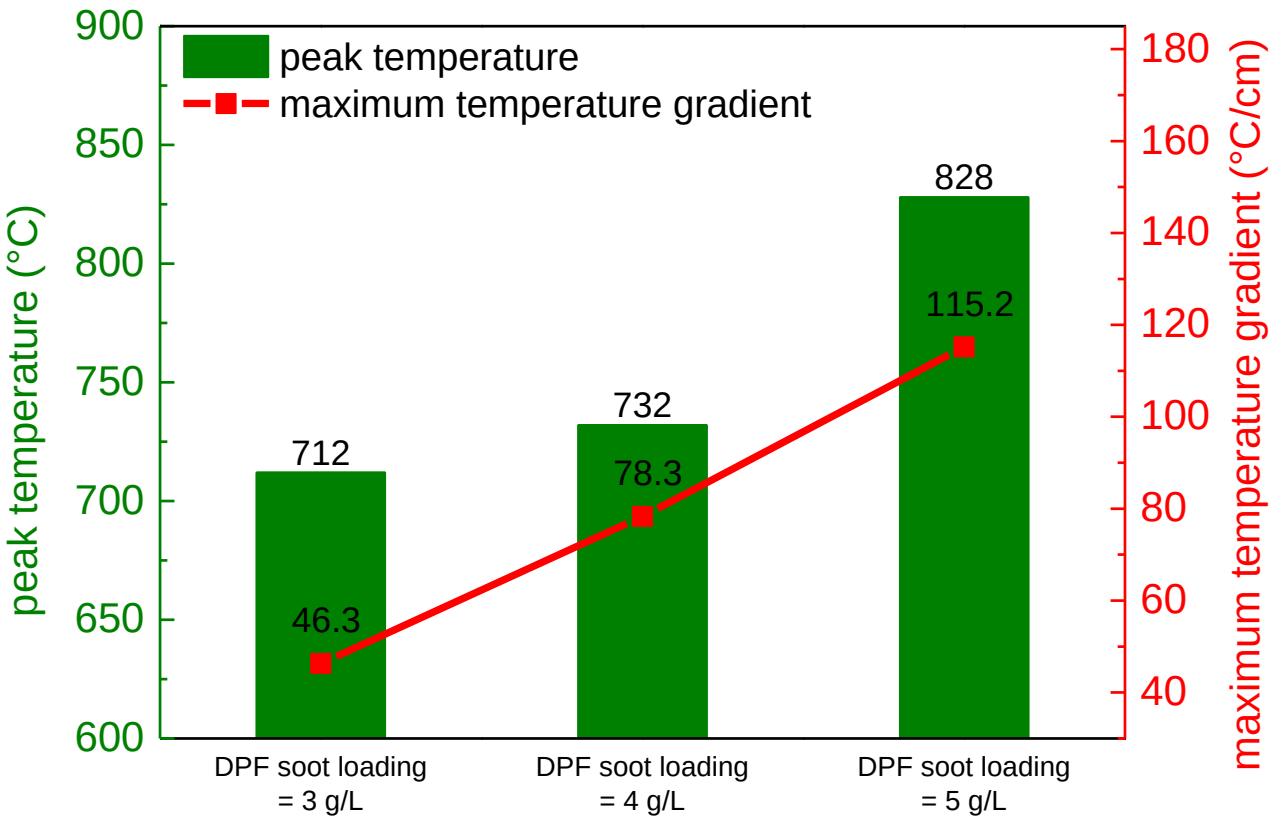
- The DPF inlet temperature during regeneration has a significant effect on the peak temperature and maximum temperature gradient, and it should be accurately controlled during active regeneration.




SV = 20,000 $h^{-1}$, DPF soot loading = 4 g/L

# Axial and Radial Uniformity Test

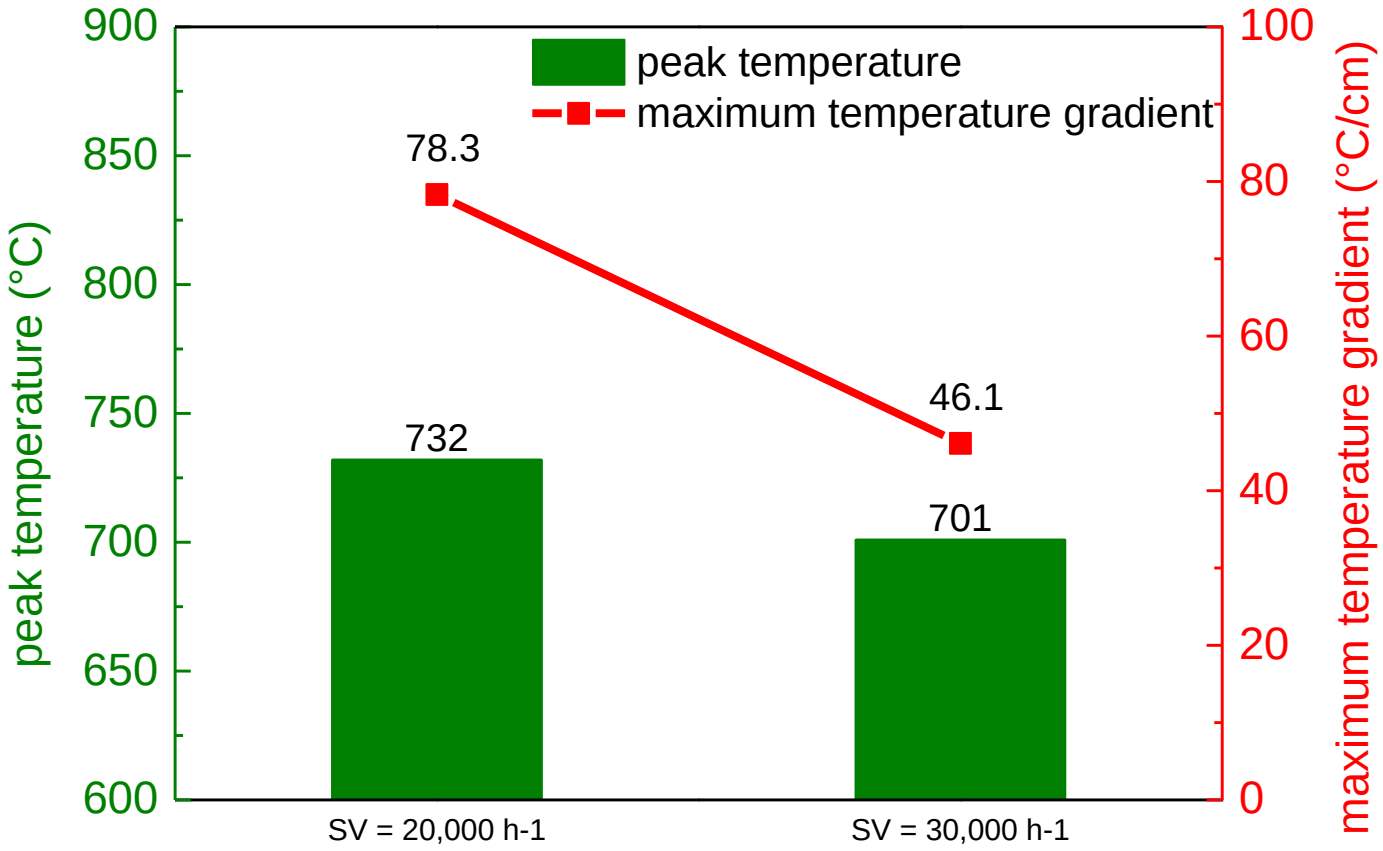
- The soot loading level for DPF regeneration triggering is an important parameter for DPF regeneration control calibration.
- The more soot loading in the DPF, the higher peak temperature and maximum temperature gradient during regeneration.




SV = 20,000 $h^{-1}$, DPF inlet temperature = 600 ℃

# Axial and Radial Uniformity Test

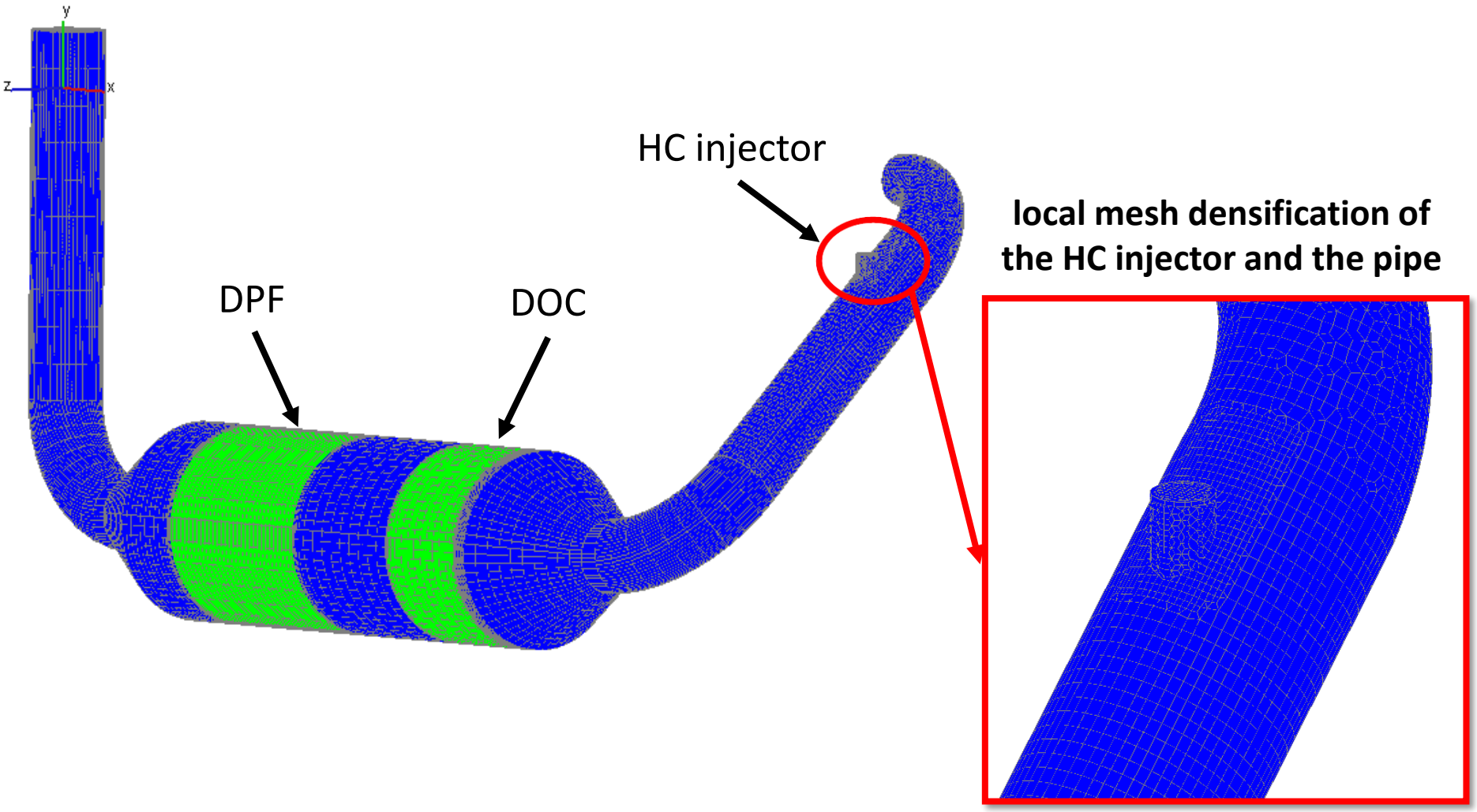
- The peak temperature and the maximum temperature gradient are both decreased at high space velocity condition due to the enhancement of the heat transfer.




DPF soot loading = 4 g/L, DPF inlet temperature = 600 ℃

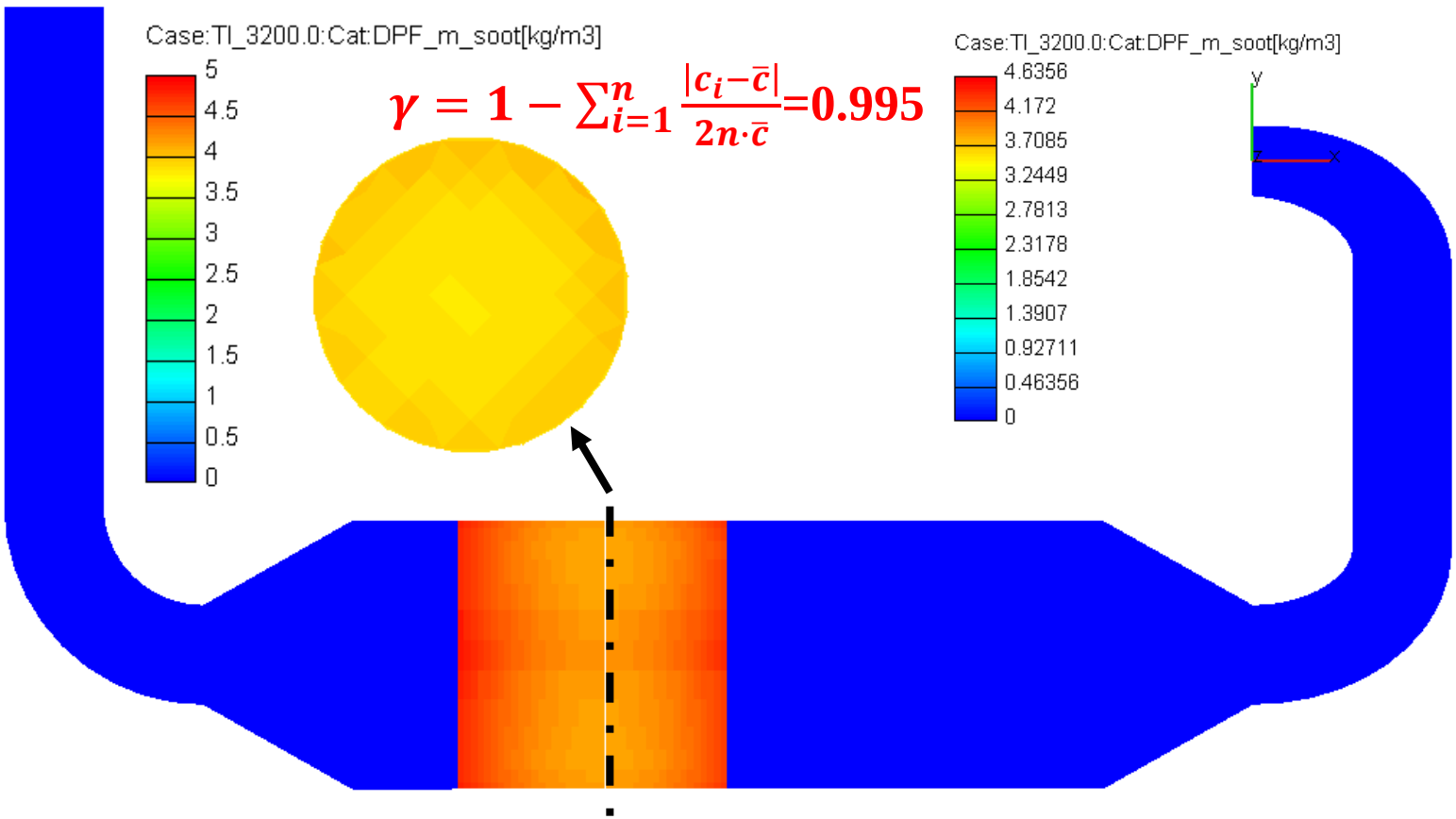
# Numerical Interpretation (CFD Modeling)

- Modeling platform: AVL FIRE
- Calculation domain and mesh generation



# Soot Loading Process Simulation

- The soot distribution in the DPF is very homogeneous, because:
  - The flow distribution after DOC is very homogeneous.
  - The soot accumulation in the DPF tends to be homogeneous, because the flow rate will be reduced due to the high flow restriction if somewhere has more soot, and then less soot will be trapped at this region.



# Diesel Spray Simulation

- HC injector parameters and spray model selection

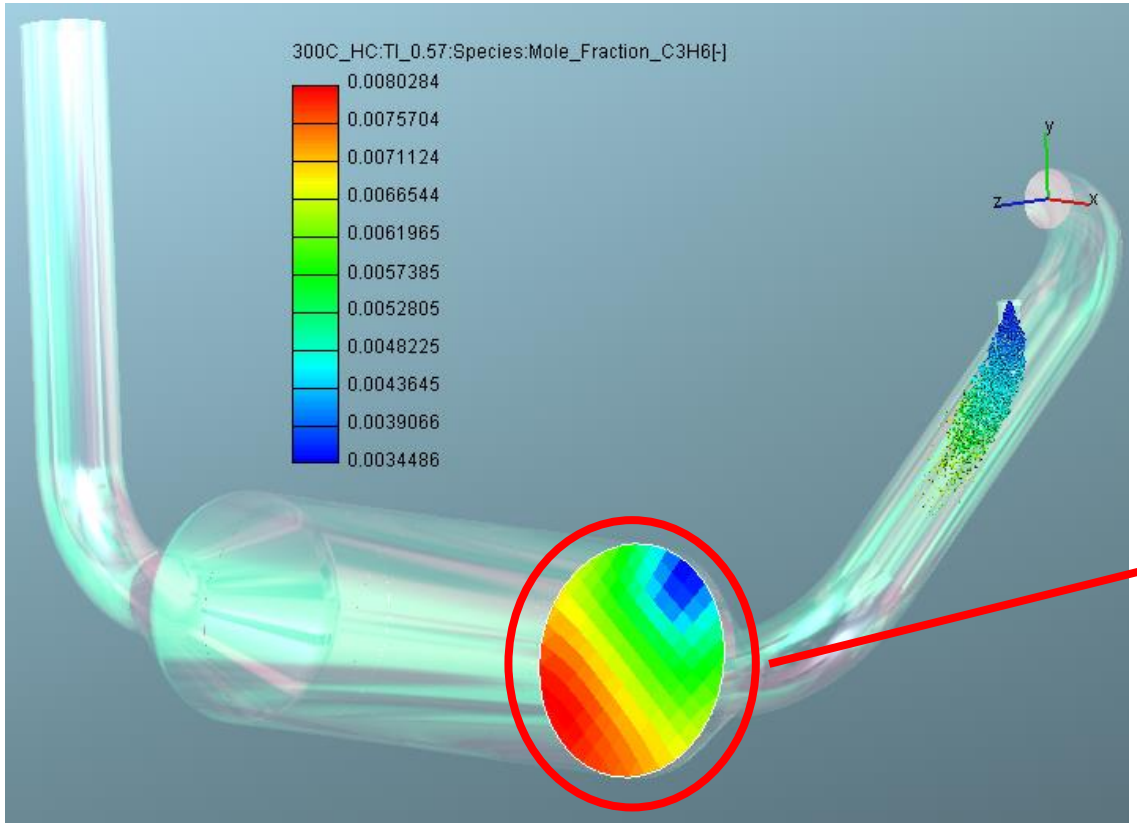
| | |
|---|---|
| Number of nozzle holes | 1 |
| Nozzle hole diameter | 0.5 mm |
| Spray cone angle | 25 ° |
| Diesel injection rate | 3.1 kg/h |
| Wall interaction model | Kuhnke model |
| Evaporation model | Dukowicz model |
| Breakup model | Wave model |

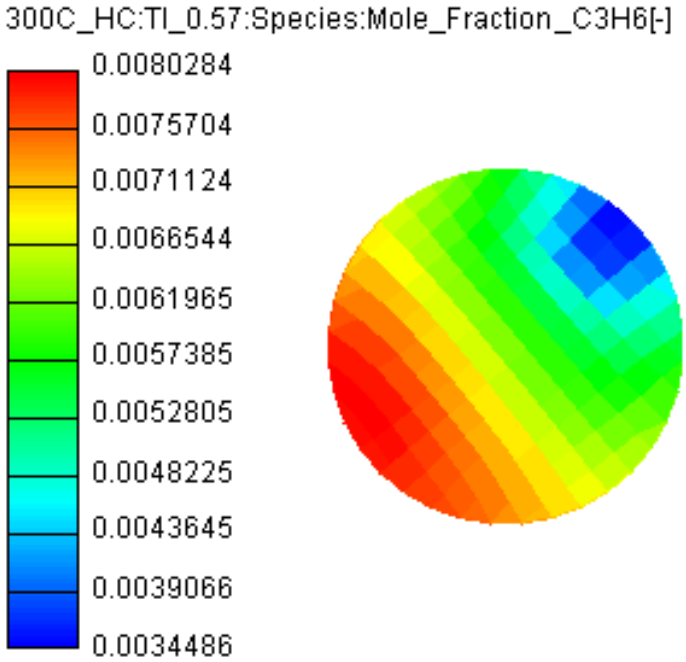
**Exhaust conditions**

| | |
|---|---|
| Exhaust mass flow | 440 kg/h |
| Exhaust temperature | 300 ℃ |
| Environment temperature | 25 ℃ |

# Diesel Spray Simulation

- The HC distribution at DOC inlet is nonuniform due to the short evaporation distance and mixing time of the diesel spray.
- The HC distribution at DOC inlet will influence the temperature distribution at the DPF inlet, thus the temperature field of the DPF during active regeneration.

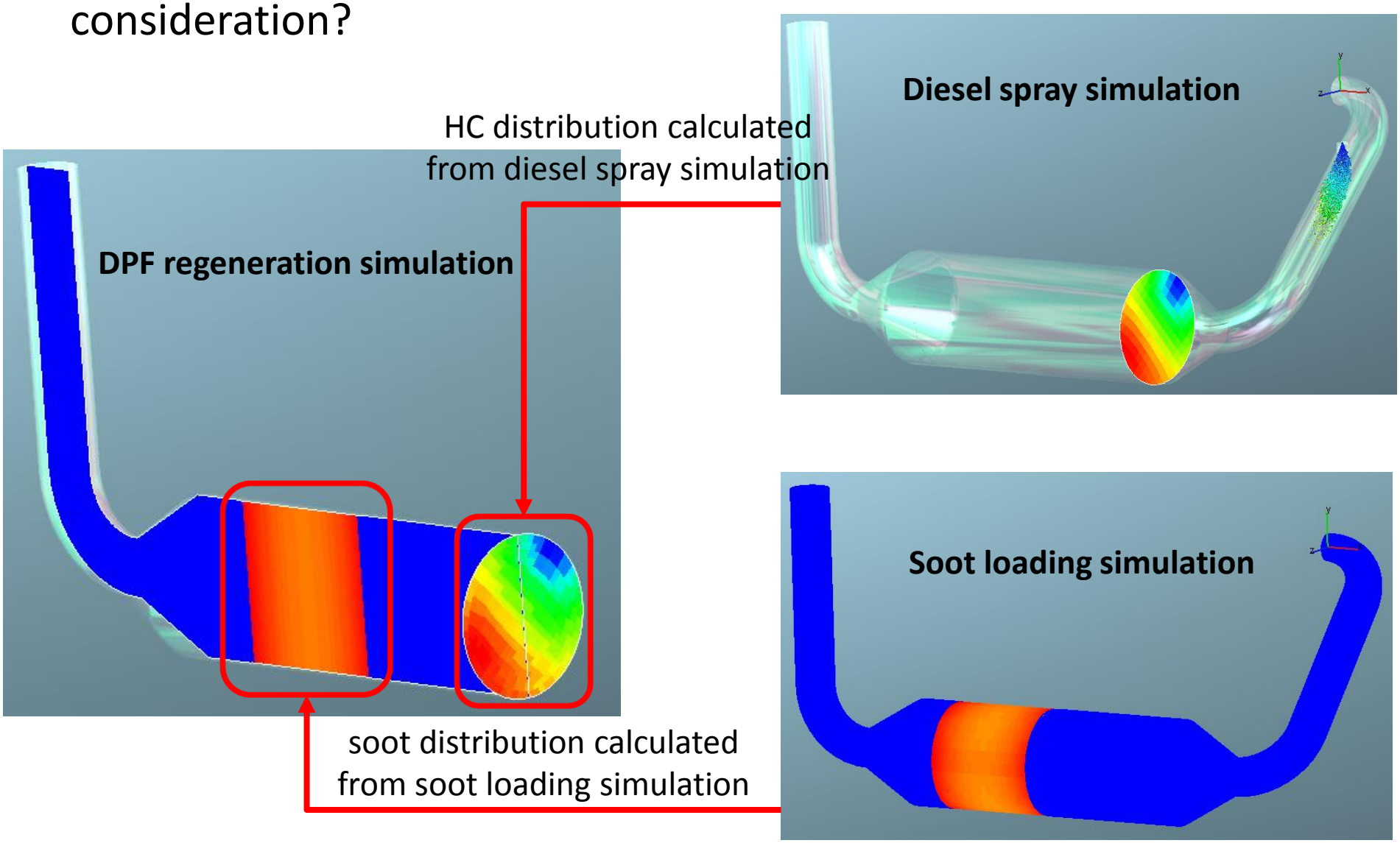



$$\gamma = 1 - \sum_{i=1}^{n} \frac{|c_i - \bar{c}|}{2n \cdot \bar{c}} = 0.926$$

# DPF Regeneration Simulation

- How to take the soot distribution and HC nonuniformity effects into consideration?



# DPF Regeneration Simulation

## DPF regeneration reactions calibration

- NO2 regeneration was ignored due to the low NO2 concentration during active regeneration, which has been mostly converted into NO at high temperature because of chemical equilibrium.

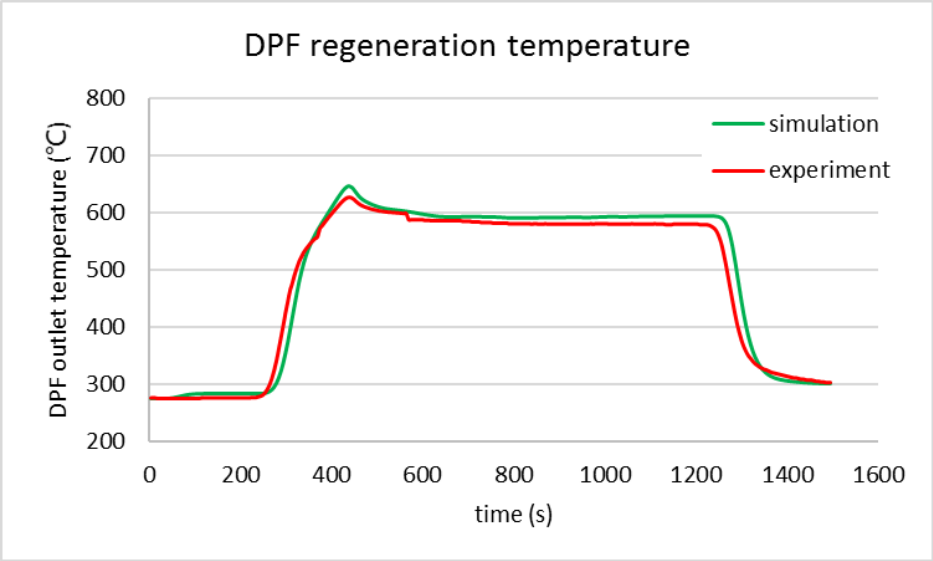
$$C(s) + {}^{1}/_{2}O_2 \xrightarrow{k_1} CO$$

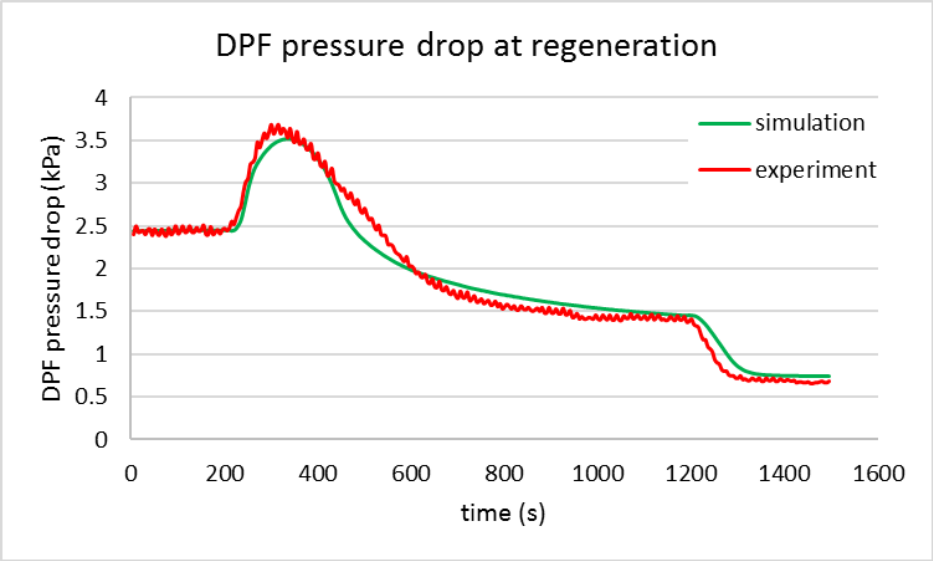
$$C(s) + O_2 \xrightarrow{k_2} CO_2$$

$$\dot{r}_1 = f_{CO} \cdot K_1 \cdot T_s \cdot e^{\left(\frac{-E_1}{R \cdot T_s}\right)} \cdot y_{O_2}$$

$$\dot{r}_2 = (1 - f_{CO}) \cdot K_1 \cdot T_s \cdot e^{\left(\frac{-E_1}{R \cdot T_s}\right)} \cdot y_{O_2}$$

$$f_{CO} = \frac{1}{1 + k_f \cdot y_{O_2}^{q_f} \cdot e^{\left(\frac{E_f}{R \cdot T_s}\right)}}$$

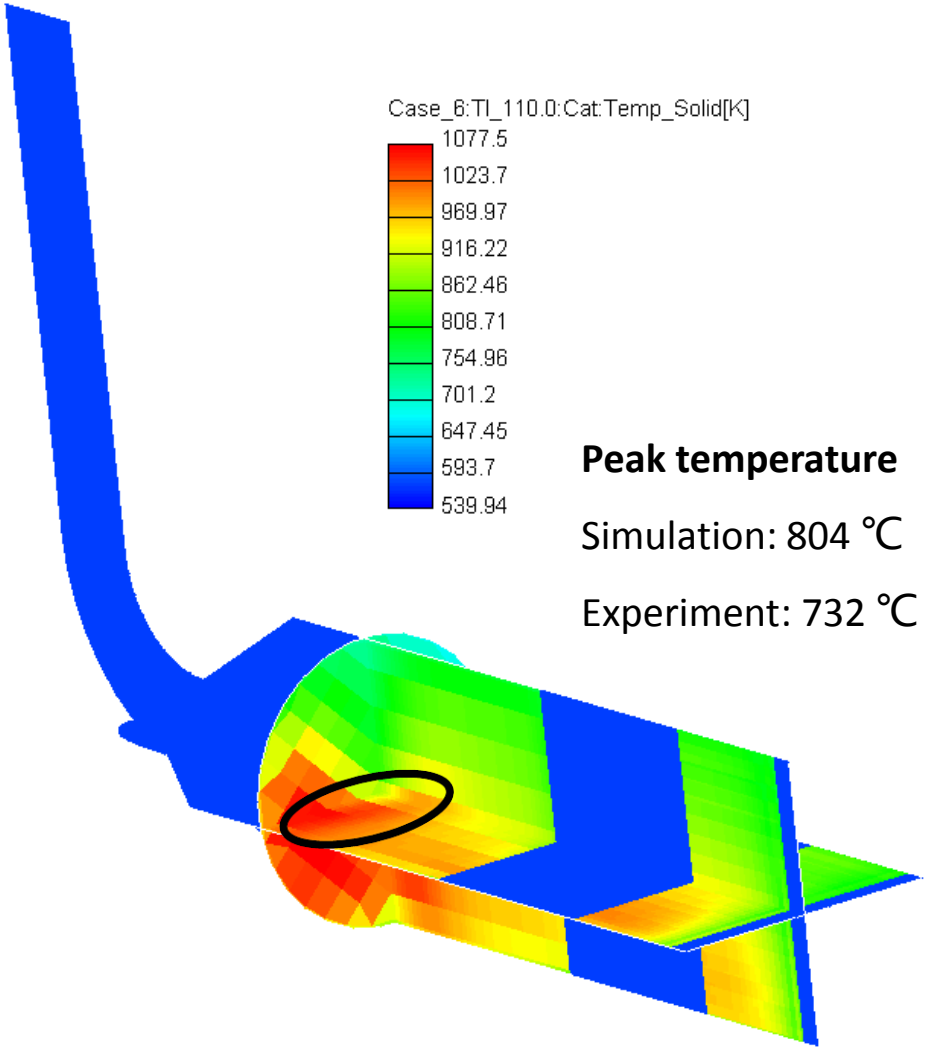


# DPF Regeneration Simulation

## DPF regeneration simulation results

Temperature

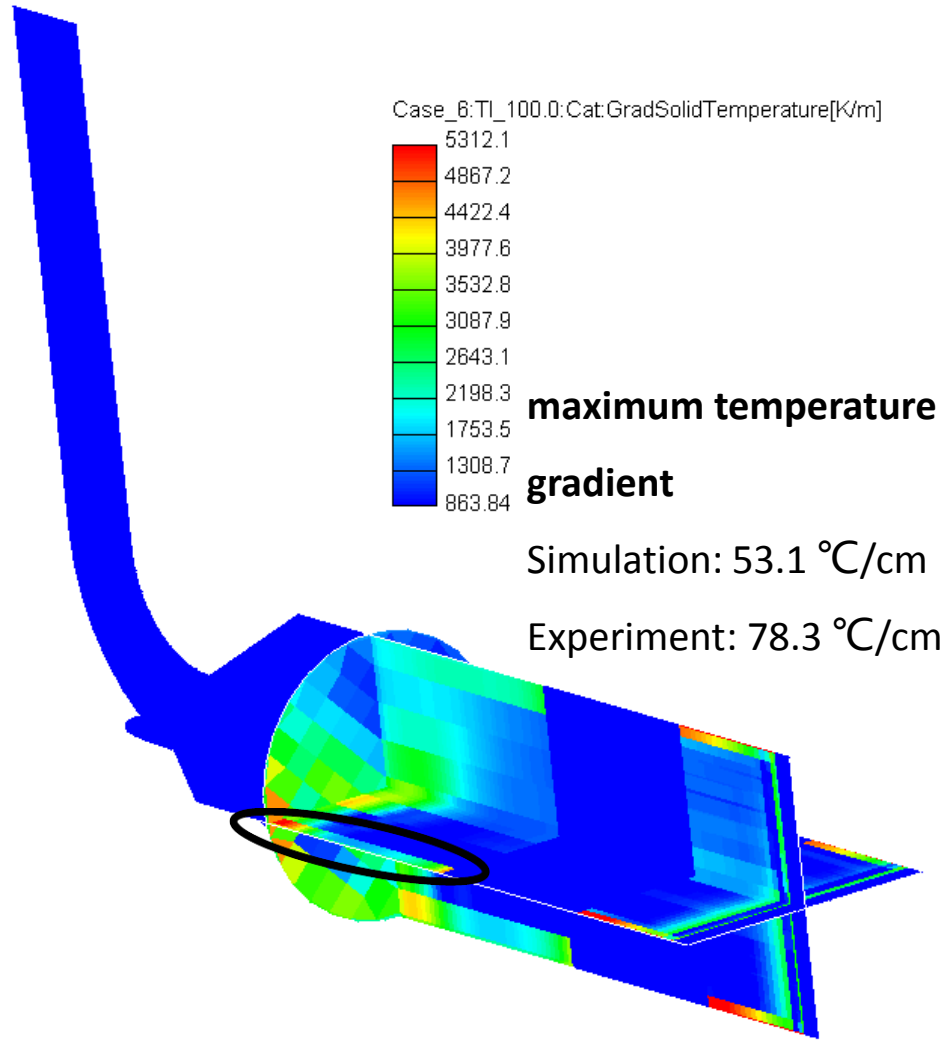



**Peak temperature**

Simulation: 804 ℃

Experiment: 732 ℃

Temperature gradient



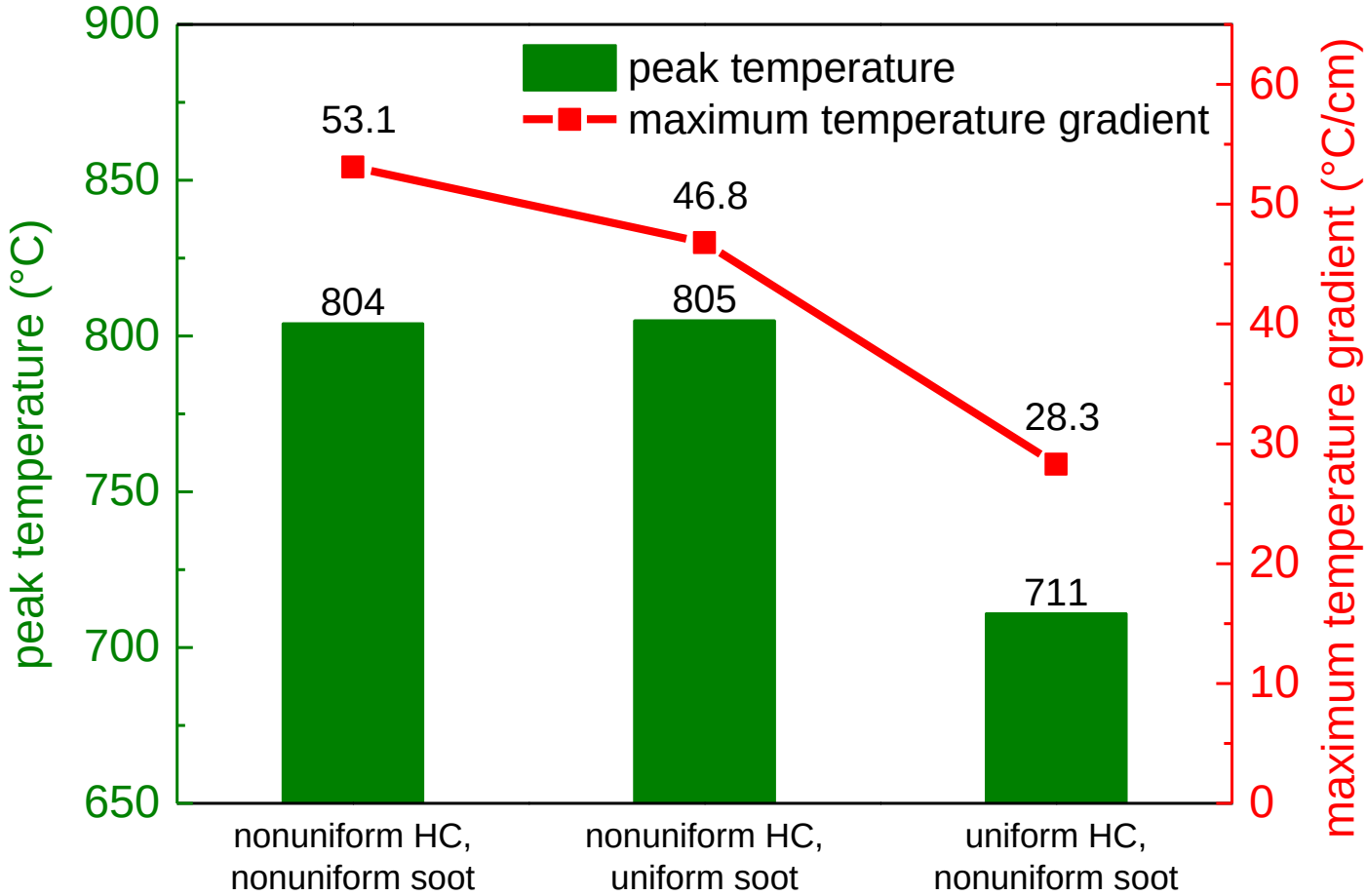

**maximum temperature gradient**

Simulation: 53.1 ℃/cm

Experiment: 78.3 ℃/cm

# DPF Regeneration Simulation

- Both the peak temperature and the maximum temperature gradient of the DPF during active regeneration can be significantly decreased with the optimization of the HC distribution at the DOC inlet.



# Summary

- The DPF temperature field during active regeneration was well studied in order to enhance the reliability and durability of the filter.
- A 3D CFD simulation, which takes the soot distribution and HC nonuniformity effect into consideration, was conducted to interpret the DPF temperature field during regeneration.
- The HC distribution at the DOC inlet has a significant effect on the DPF temperature filed during regeneration, and it should be well optimized.
- The DPF temperature field during DTI (drop to idle) regeneration should be studied in the future work, which is much more critical for the DPF reliability and durability than the steady state regeneration.

# Acknowledgements


## Tsinghua University

- Chuandong Li, Guoyang Wang, Bo Yang, Yang Liu, Jianhua Xiao, Feng Yan, Lei Deng

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## MIT

- Dr. Victor W. Wong

# Q&A

# Thank you!

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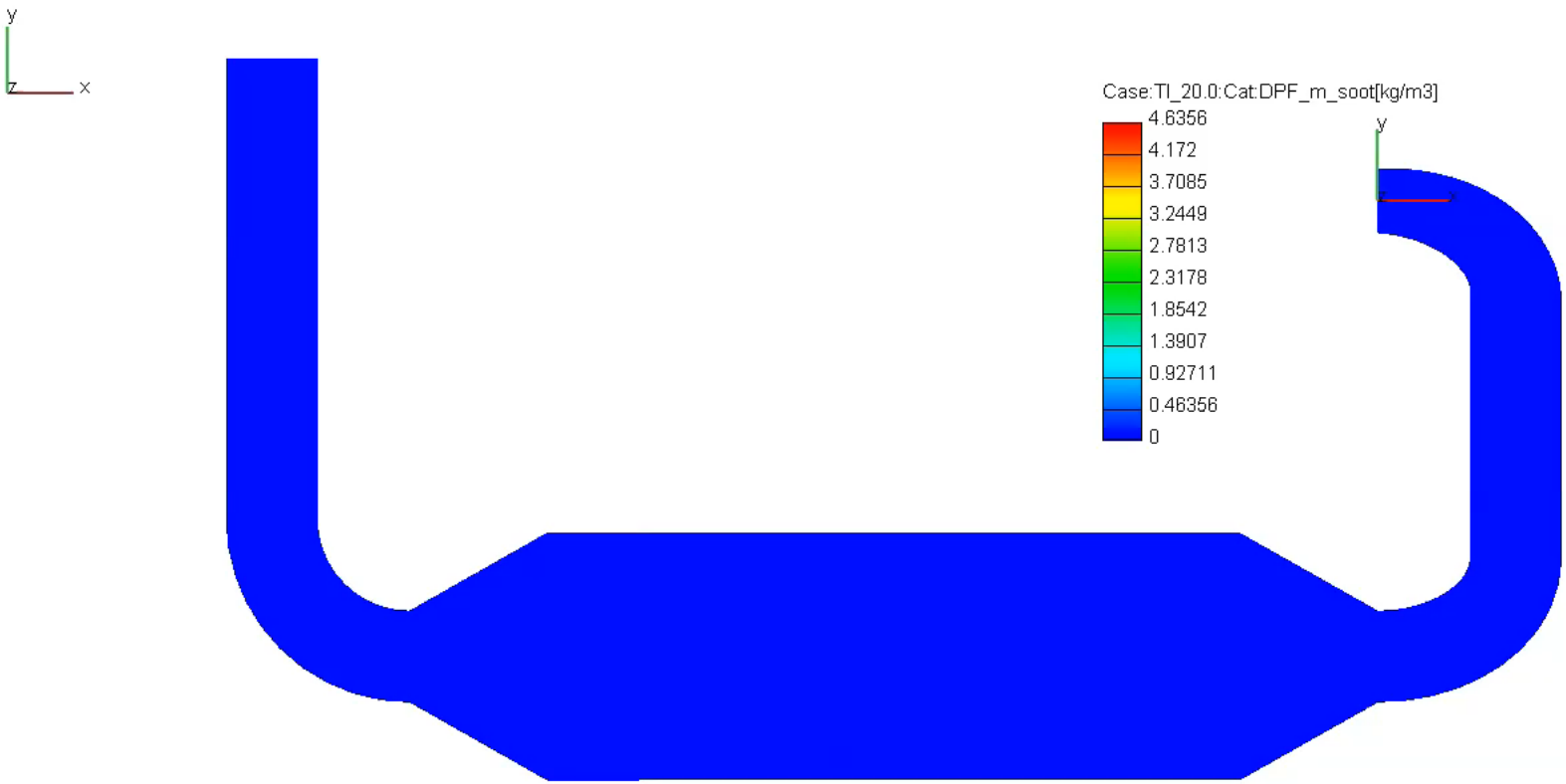
# Back up

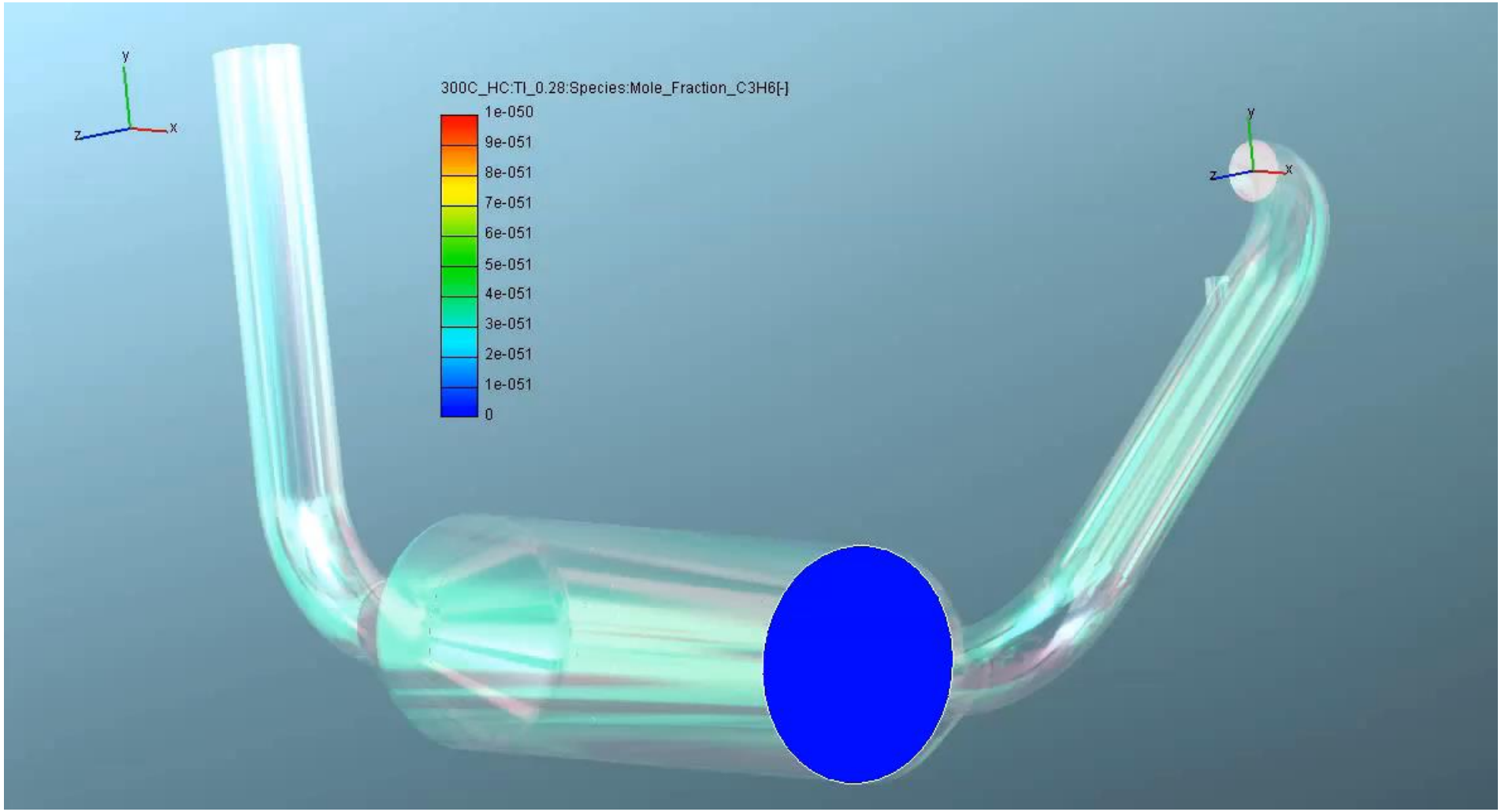
# Soot Loading Process Simulation

- The soot loading process



# Diesel Spray Simulation

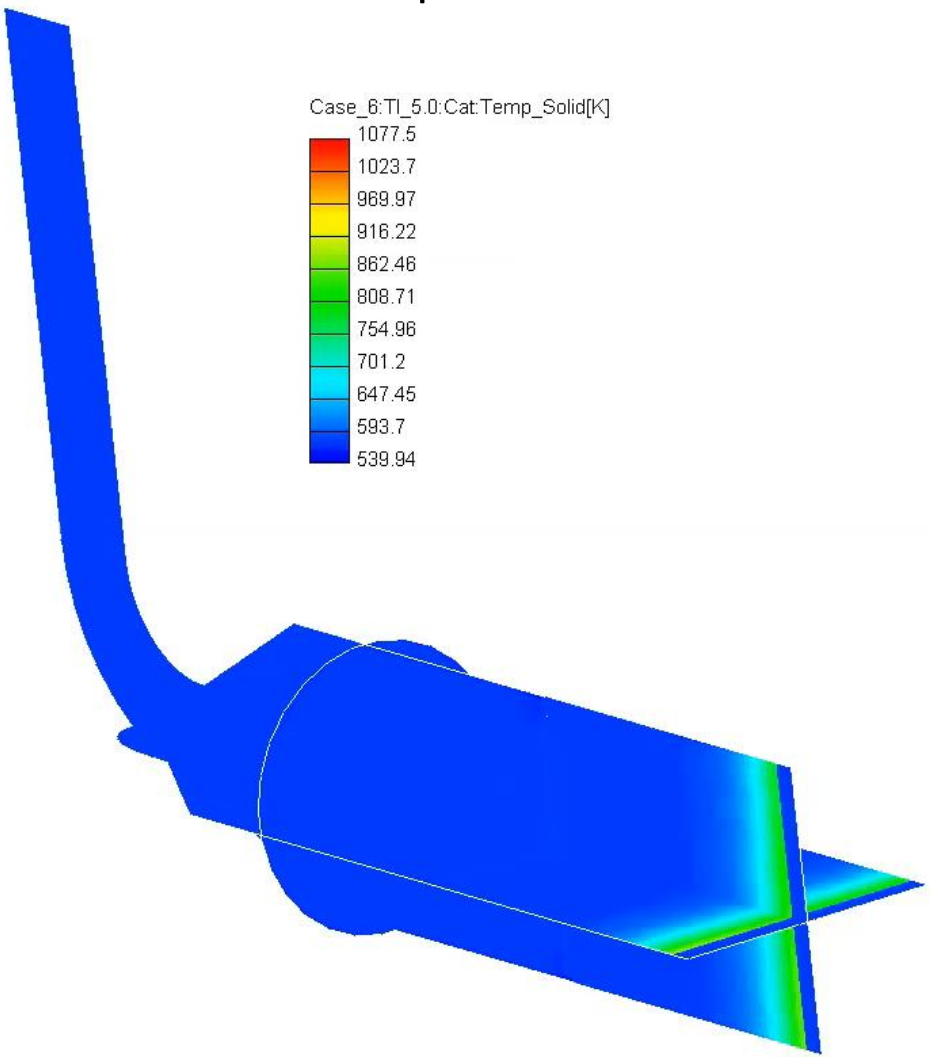
- Diesel spray



# DPF Regeneration Simulation

- DPF regeneration

Temperature




Temperature gradient