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# GT-POWER 后处理功能在高排放柴油发动机开发中的应用



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GT  王新校

# 概述

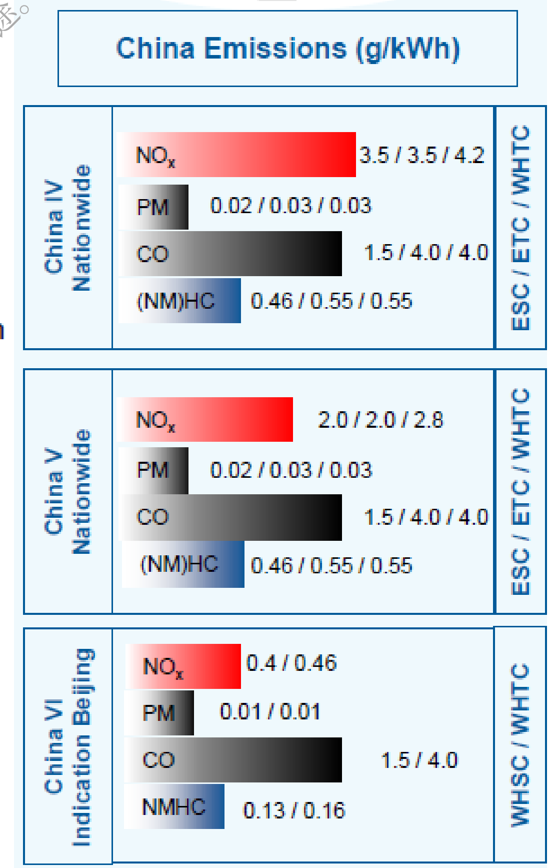
- 中国排放法规升级以及主机厂后处理应对策略介绍
- GT软件后处理功能简单介绍
- 先进的CDPF工程应用方法介绍
- 总结

# 中国排放法规升级以及后处理应对策略

# 重型车排放法规升级

| | China IV | China V |
|---|---|---|
| Test procedure | ESC, ETC and WHTC | ESC, ETC and WHTC |
| Sulfur content | 50 mg/kg | 10 mg/kg |
| $NO_x$ emissions | 3.5, 3.5 and 4.2 g/kWh | 2.0, 2.0 and 2.8 g/kWh |
| PM emissions | 0.02, 0.03 and 0.03 g/kWh | 0.02, 0.03 and 0.03 g/kWh |
| $NH_3$ slip (SCR) | 25 ppm | 25 ppm |
| Fuel Consumption | ☑ | ☑ |
| ESC 3 points | $NO_x$ | $NO_x$ |
| In-service conformity | PEMS (BJ) | PEMS (BJ) |
| Durability | ☑ N3 (>16t): 500,000 km | ☑ N3 (>16t): 500,000 km |
| OBD | ☑ (OBD Stage 1) | ☑ (OBD Stage 2) |

## Limits

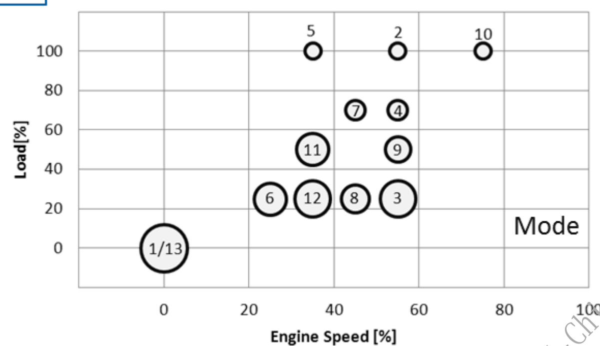



Generic view, no exemptions or phase in requirements considered

# 欧六道路用排放法规

## WHSC

averaged WHSC power ~25% of max. engine power



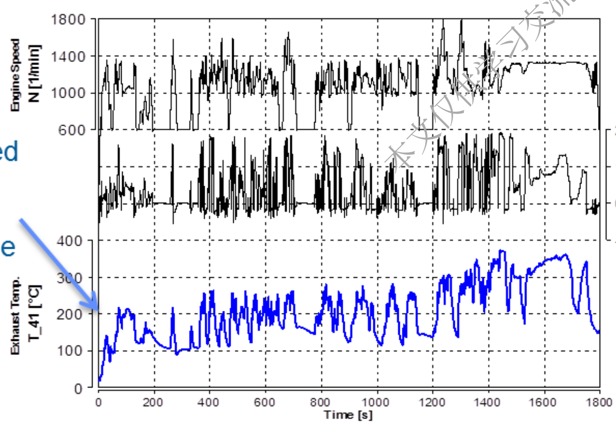

| Mode | Normalized Speed (per cent) | Normalized Torque (per cent) | Mode length (s) incl. 20 s ramp |
|---|---|---|---|
| 1 | 0 | 0 | 210 |
| 2 | 55 | 100 | 50 |
| 3 | 55 | 25 | 250 |
| 4 | 55 | 70 | 75 |
| 5 | 35 | 100 | 50 |
| 6 | 25 | 25 | 200 |
| 7 | 45 | 70 | 75 |
| 8 | 45 | 25 | 150 |
| 9 | 55 | 50 | 125 |
| 10 | 75 | 100 | 50 |
| 11 | 35 | 50 | 200 |
| 12 | 35 | 25 | 250 |
| 13 | 0 | 0 | 210 |
| Sum | | | 1895 |

## WHTC

averaged WHTC power ~19% of max. engine power

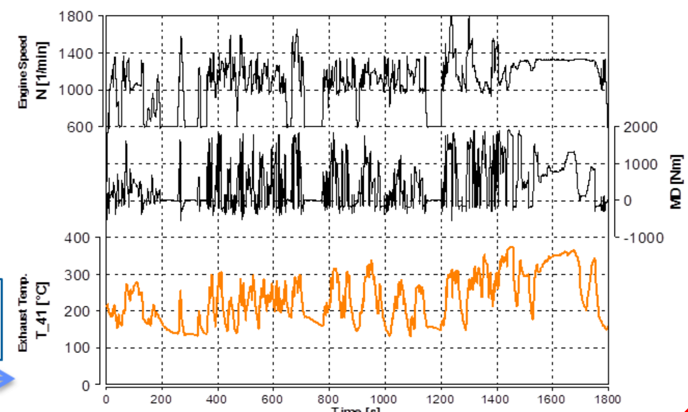
cold WHTC – 14% weighted

started with cold engine




10min soak time

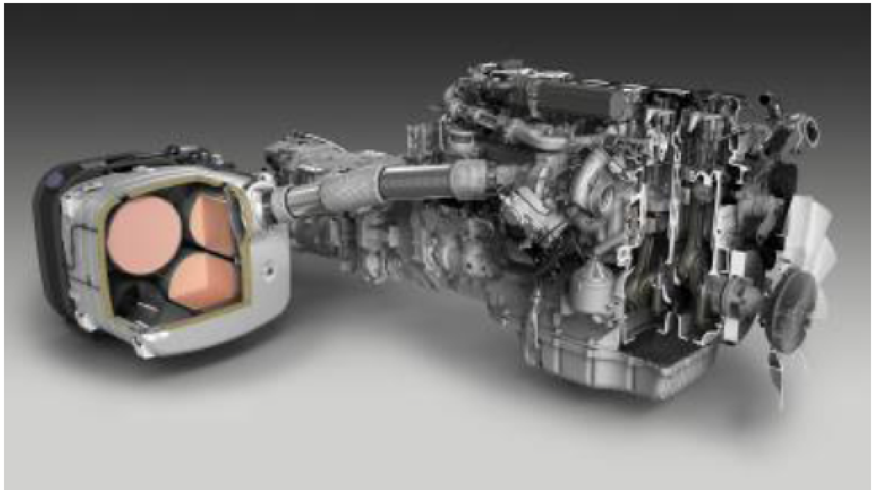
hot WHTC – 86% weighted



# 主要OEM后处理应对路线

## SCANIA EU6 13L

- 440 and 480 hp 12.7-litre Euro VI engines
- fuel consumption of fuel equivalent to Scania Euro V engines
- combined all the new technologies that Scania has developed in recent years: EGR, VTG, common-rail high-pressure fuel injection (Scania XPI, up to 2400 bar)
- Compact insulated silencer design
- Design DOC-DPF + 2x SCR-ASC
- 3-4% AdBlue consumption
- 370 & 410 hp as well as 16L V8 engines announced on IAA



# VOLVO-EU6平台介绍

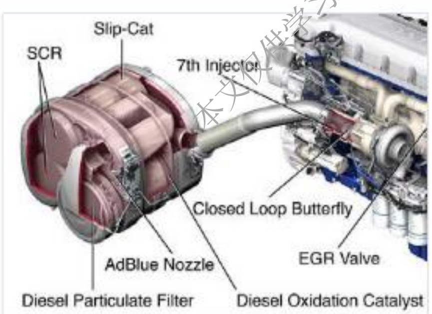
## HDEP, Eu6 products

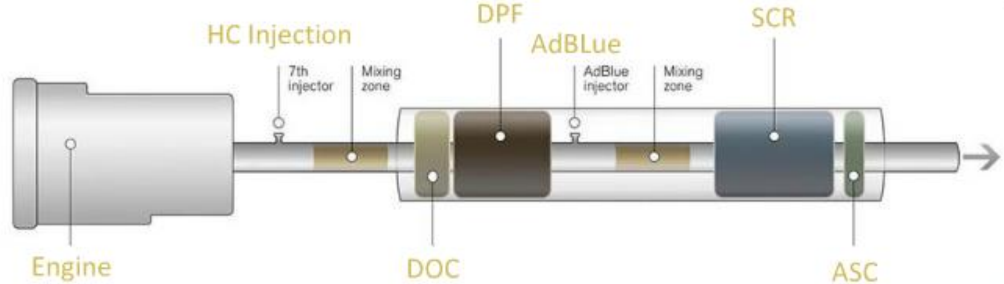
**HDE11**
10.8 L
[330..460] HP
Up to 2250Nm @ 1000rpm

**HDE13**
12,8 L
[420..540] HP
Up to 2600Nm @ 1000rpm

**HDE16**
16,1 L
[540..750] HP
Up to 3550Nm @ 950rpm

EATS Platform



# VOLVO EU6 13L

D13K460, 13L, 460hp (2300 Nm)

Pump-Line-Nozzle injection (up to 2000 bar)

Non-cooled EGR
- used at low load to heat-up system
- turned off at elevated loads

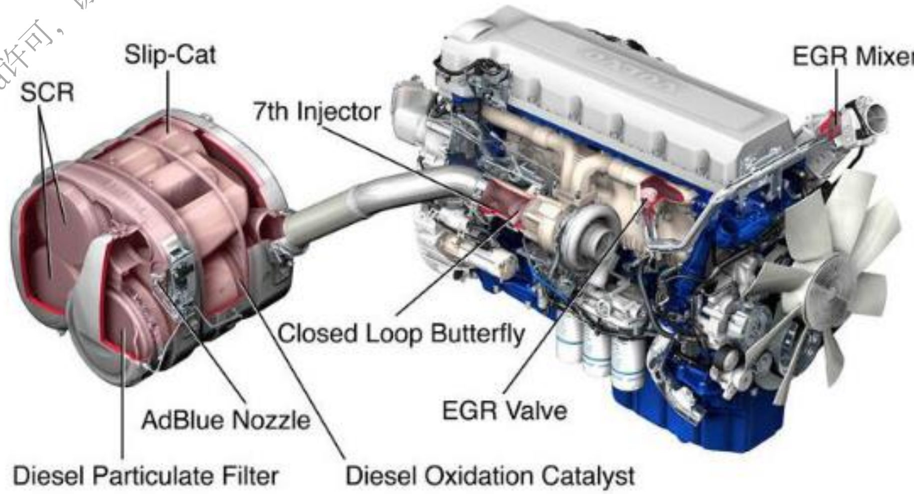
7th injector

2stage TC (Turbocompound)

Design DOC-DPF + 2x SCR-ASC

Fuel consumption "almost on par" with D13C (EuroV)

Future engine expected to have CR



# DAF 13liter EU6

- 12.9 litre Euro 6 PACCAR MX-13 engine with outputs of 300 kW/410 hp, 340 kW/460 hp and 375 kW/510 hp
- Newly designed engine block for optimum stiffness and integration
- High pressure common rail fuel injection for injection pressures of up to 2,500 bar
- Turbo charger with variable geometry
- combination of exhaust gas after-treatment technologies, such as an SCR converter and an active soot filter
- allow as much passive regeneration as possible
- exhaust manifold, as well as the most essential parts of the exhaust system, have been encapsulated.
- A 7th injector, positioned behind the turbo and ahead of the soot filter, has been added to the engine to switch to active regen

# Cummins –EU6

6.7 litre engine range extends up to 310 ps for truck and coach installations, and 280 ps for bus applications. Peak torque remains 1100 Nm.

4.5 litre engine range extends 210 ps for truck and 200 ps for bus installations, delivers a strong peak torque of 760 Nm.

cooled exhaust gas recirculation (EGR) with variable geometry turbocharging (VGT)

SCR design uses Copper Zeolite technology for very high conversion efficiency, even at low temperatures. The CPF system will manage re-generation events without the need for driver intervention.

The airless Adblue dosing nozzle is integrated in the system for improved reliability and durability.

# North American Truck- ISX15 And ISX12 Engines

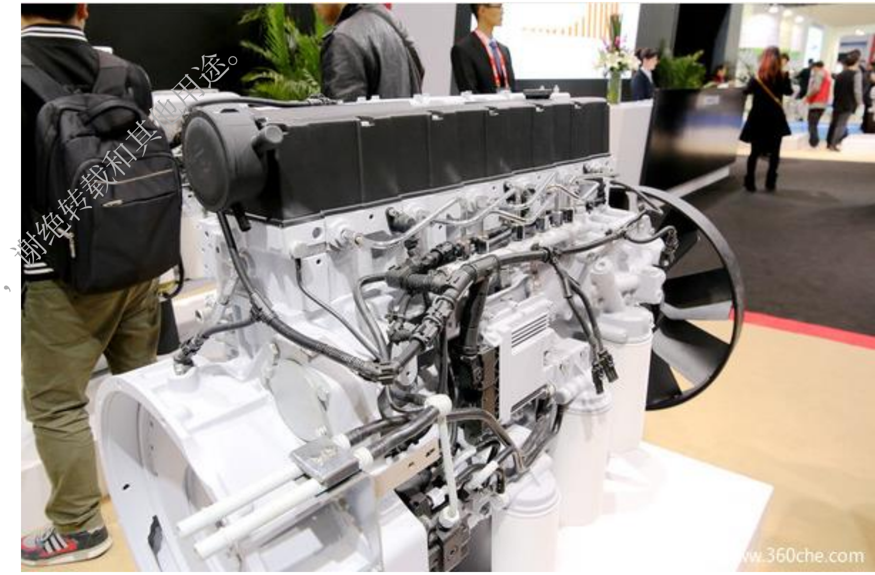
**Aftertreatment Extended Coverage**

**The coverage includes Cummins-supplied aftertreatment components, including:**

- **Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and SCR assemblies**
- **Hydrocarbon dosing system**
- **Diesel Exhaust Fluid (DEF) dosing system**
- **Aftertreatment controls**

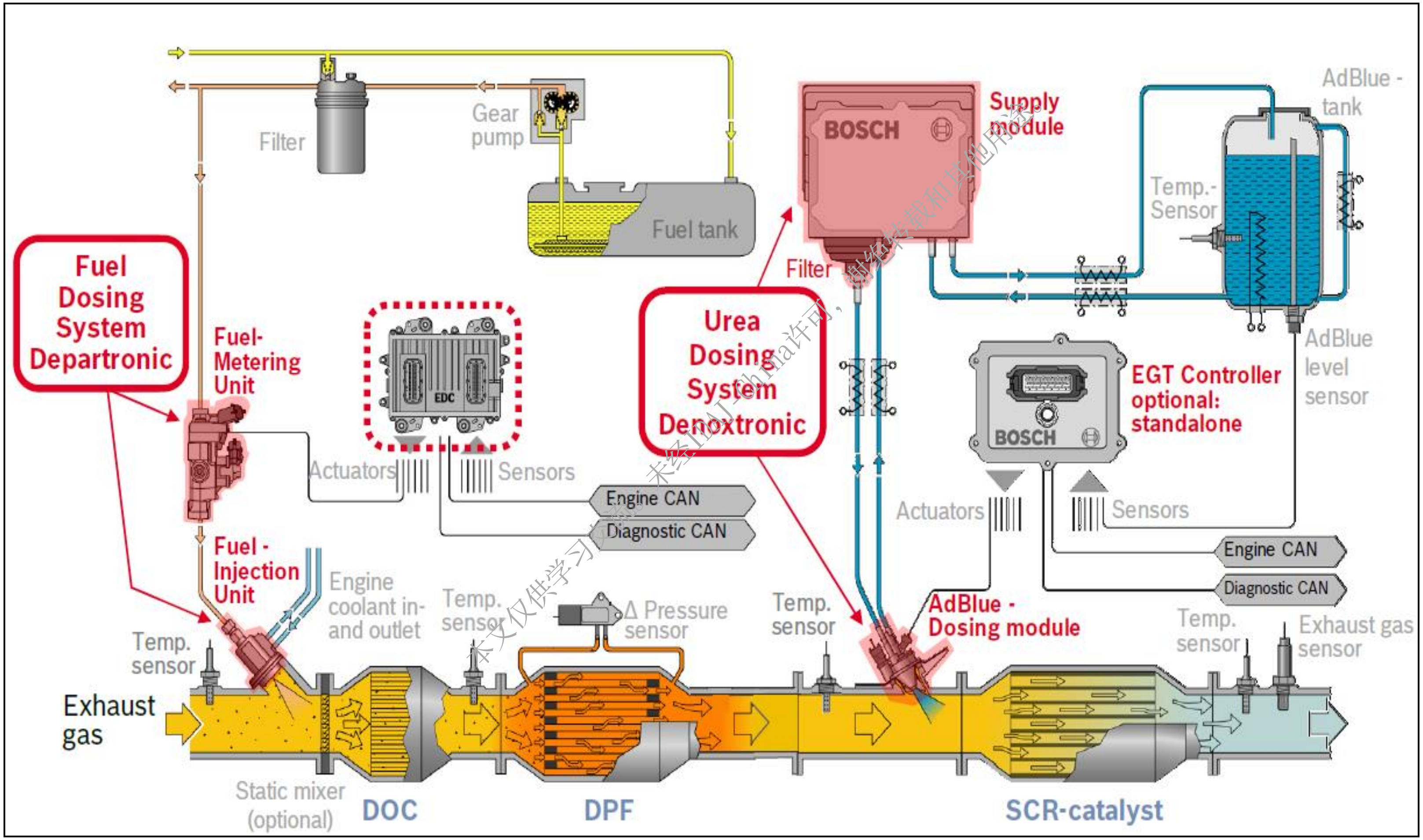
# 潍柴国六发动机


WP10-EGR+DOC+DPF+SCR+ASC




WP7-EGR+DOC+DPF+SCR+ASC

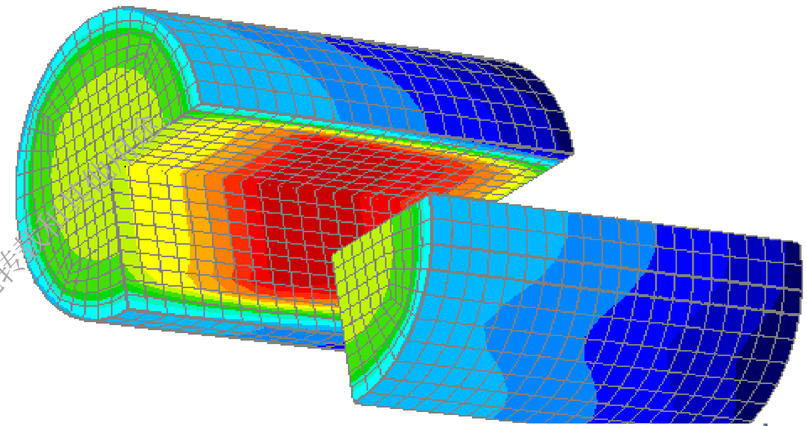
# 后处理硬件控制系统图



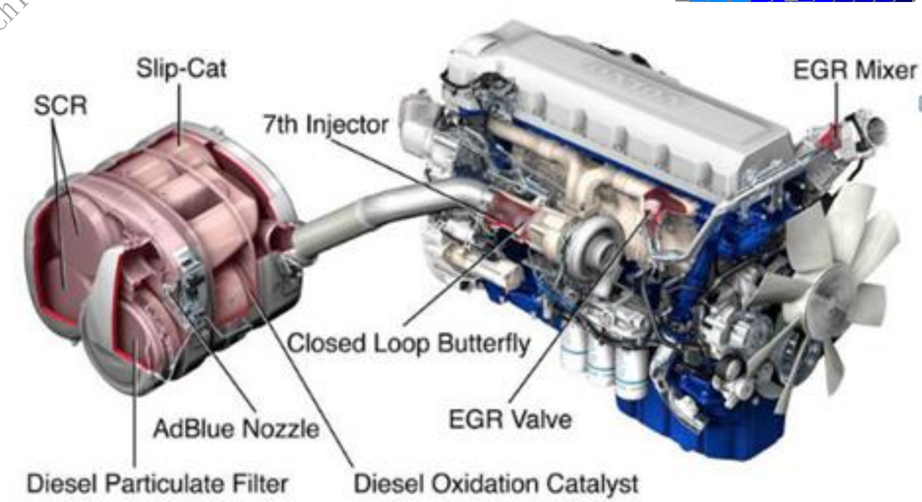
Filter
Gear pump
Fuel tank
Fuel Dosing System Departronic
Fuel-Metering Unit
EDC
Actuators
Sensors
Engine CAN
Diagnostic CAN
Fuel - Injection Unit
Engine coolant in- and outlet
Temp. sensor
Δ Pressure sensor
Exhaust gas
Static mixer (optional)
DOC
DPF
SCR-catalyst
BOSCH
Supply module
Filter
Urea Dosing System Denoxtronic
AdBlue - tank
Temp.- Sensor
AdBlue level sensor
EGT Controller optional: standalone
AdBlue - Dosing module
Exhaust gas sensor

# GT软件后处理功能介绍

# GT软件后处理功能介绍



GT后处理模拟包含当前所有应用的后处理系统：
•汽油机与柴油机
•通流式与壁流式系统
•支持用户柔性的催化反应机理输入，满足不同客户的需求
•License与GT-power相同，不需要额外购买许可
➢后处理装置包括：
•TWC - Three Way Catalyst
•DOC - Diesel Oxidation Catalyst
•SCR - Selective Catalytic Reduction
•LNT - Lean NOx Trap
•DPF - Diesel Particulate Filter
•CDPF/CSF - Catalyzed DPF, Catalyzed Soot F
•SCR-F - SCR coated Filter/DPF



# 反应机理柔性输入-非常方便

- 用户可以通过输入界面控制反应机理，任意的修改添加关闭或打开特定反应
- 用户不需要输入代码

| Include Reaction | Associated Site Element | Reactants | Products | Pre-exponent Multiplier | Temperature Exponent | Activation Temperature or Energy | Concentration Expressions | Coverage Expressions |
|---|---|---|---|---|---|---|---|---|
| | | | | | | kcal/kmol | | |
| ☑ | Zeolite1 | Z1 + NH3 | Z1NH3 | 0.657 | 0 | 0 | {NH3} | A(1) |
| ☑ | Zeolite1 | Z1NH3 | Z1 + NH3 | 13.252 | 0 | 0 | G(1) | A(2) |
| ☑ | Zeolite1 | 4Z1NH3 + 3O2 | 2N2 + 6H2O + 4Z1 | 3.04E+08 | 0 | 42470 | {O2}^0.5*G(2)^0.5 | A(2) |
| ☑ | Zeolite1 | 4Z1NH3 + 4NO + O2 | 4N2 + 6H2O + 4Z1 | 1.69E+05 | 0 | 11640 | {NO}*{O2}^0.5*G(2)... | A(2) |
| ☑ | Zeolite1 | NO + 0.5O2 | NO2 | 56.33 | 0 | 7420 | {NO}*{O2}^0.5*G(2)... | 1 |
| ☑ | Zeolite1 | 4Z1NH3 + 2NO + 2NO2 | 4N2 + 6H2O + 4Z1 | 1.53E+15 | 0 | 27020 | {NO2}*{NO} | A(2) |
| ☑ | Zeolite1 | 8Z1NH3 + 6NO2 | 7N2 + 12H2O + 8Z1 | 7.28E+11 | 0 | 30000 | {NO2} | A(2) |
| ☑ | Zeolite2 | Z2 + NH3 | Z2NH3 | 40 | 0 | 0 | {NH3} | A(3) |
| ☑ | Zeolite2 | Z2NH3 | Z2 + NH3 | 19731600 | 0 | 22044 | 1 | A(4) |
| ☑ | Zeolite2 | 4Z2NH3 + 3O2 | 2N2 + 6H2O + 4Z2 | 3.04E+08 | 0 | 42470 | {O2}^0.5*G(2)^0.5 | A(4) |

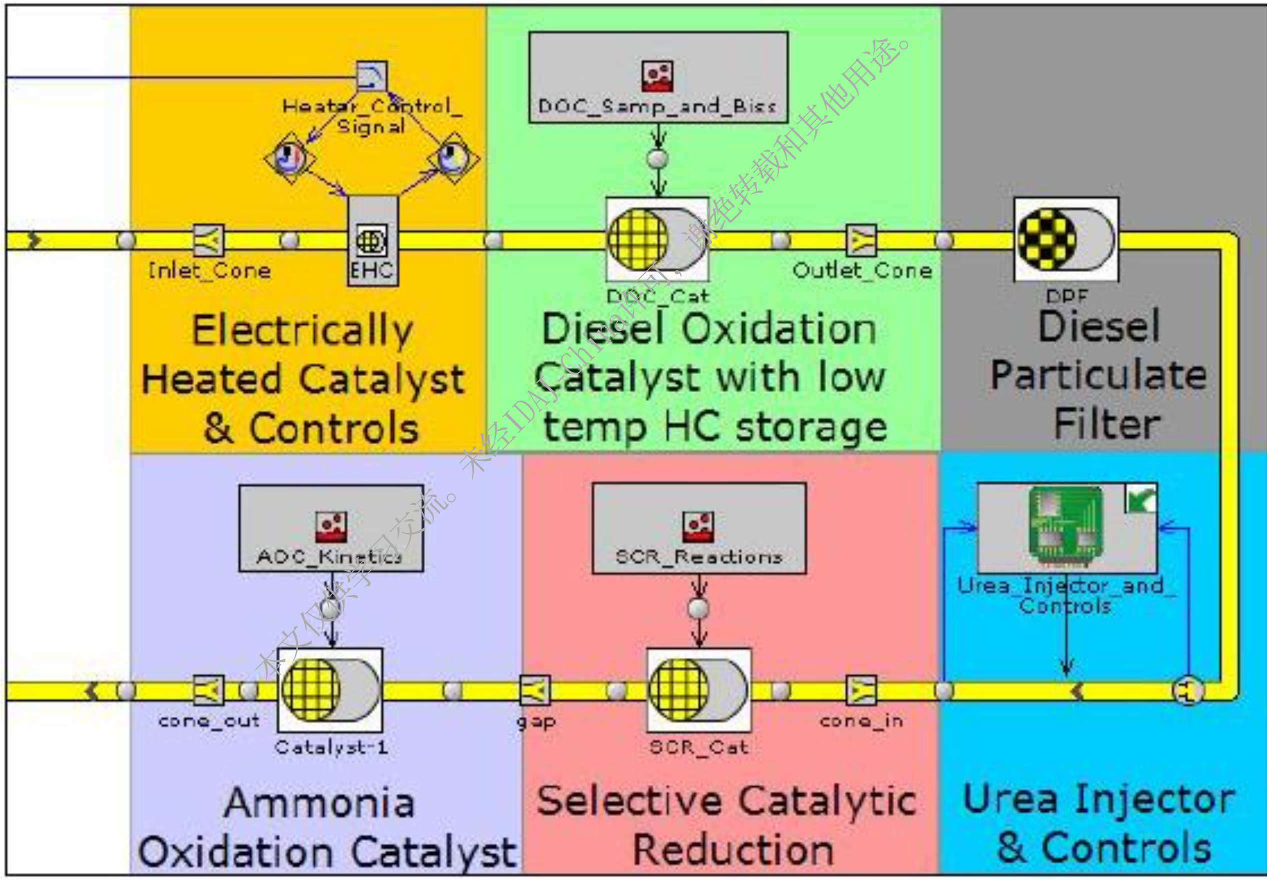
支持多活化位输入，支持非Arrhenius rates

| Site Element Name | | PGM | cerium | barium | barium_low |
|---|---|---|---|---|---|
| Site Density Option #1 | | | | | |
| Active Surface Site Density | mol/m^3 | ign | 90 | 14 | 14 |
| Site Density Option #2 | | | | | |
| Loading of Site Element | g/ft^3 | 113 | ign | ign | ign |
| Atomic Weight (g/mol) | | 158 | ign | ign | ign |
| Dispersion Factor | | 0.12 | ign | ign | ign |

Ammonia desorption rate, function of $NH_3$ coverage, A(2) $= \theta_{NH_3}$

exp(-39564.2/8.314/T*(1-0.89*A(2)))

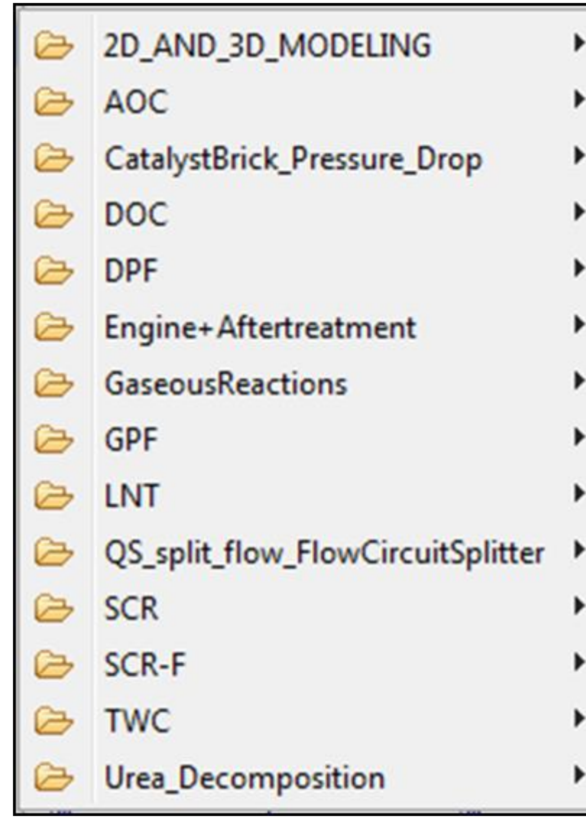
# Catalyst and Particulate Filter Modeling Overview
# 支持所有的流通式和壁流式的后处理装置



# 先进的反应机理模型 – Example Models

GT-SUITE安装文件包含例子模型-每一种常用的后处理装置都有

每一个例子基于文献的反应机理输入或者基于文献数据进行了标定，用户可以在基础上面进行修改

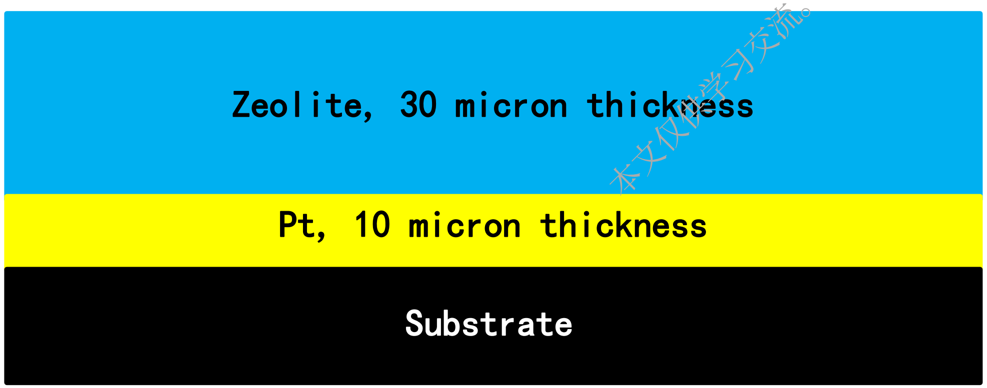


# 双活化层反应器模拟


对两个催化剂反应层的反应动力学机理都输入到单个 `SurfaceReactions` 模板中

- 对反应的数目和反应不做限制
- 反应顺序是任意的

## 例如：an SCR-coated AOC



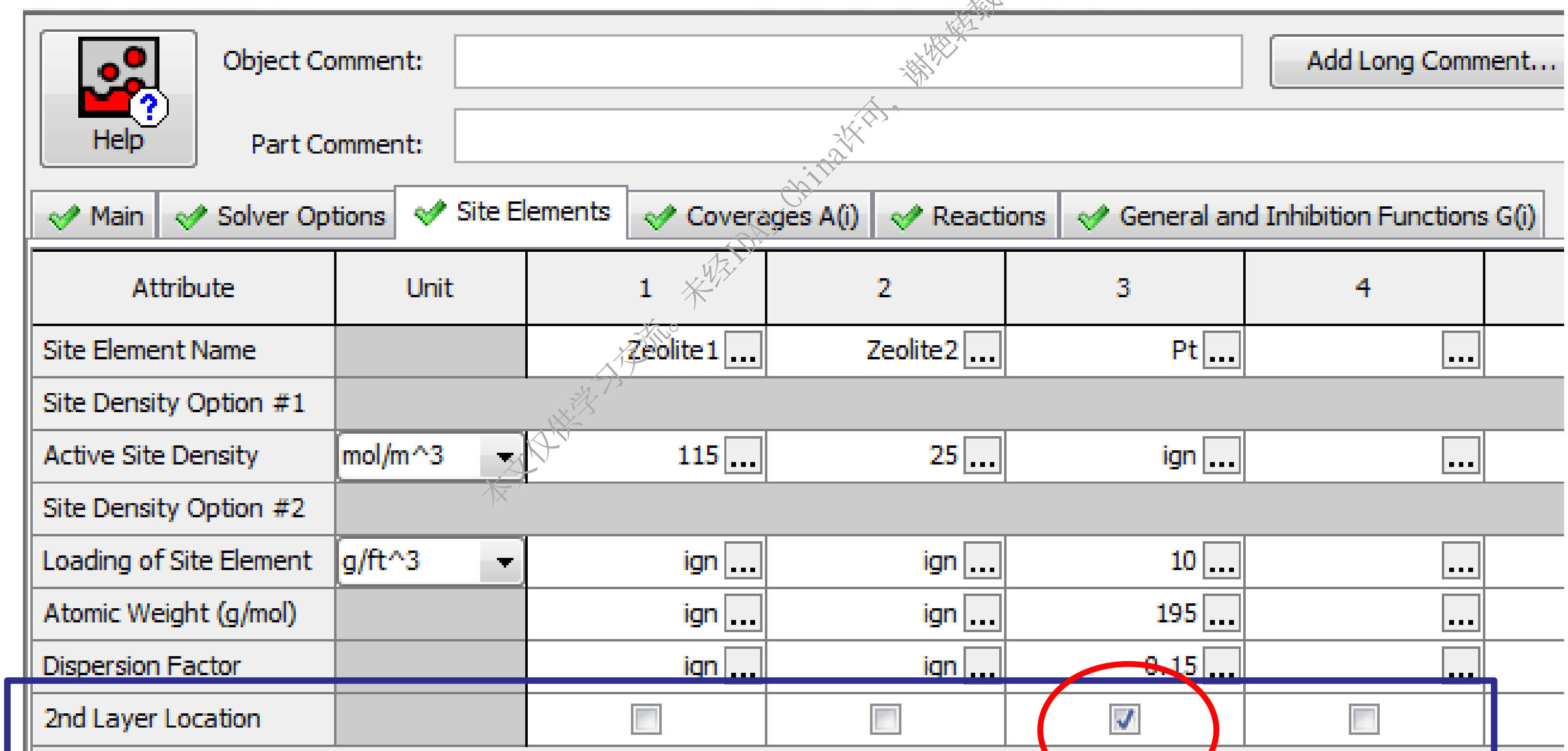

| Attribute | Include Reaction | Associated Site Element | Reactants | Products |
|---|---|---|---|---|
| Unit | | | | |
| 1 | ☑ | Zeolite1 | Z1 + NH3 | Z1NH3 |
| 2 | ☑ | Zeolite1 | Z1NH3 | Z1 + NH3 |
| 3 | ☑ | Zeolite1 | 4Z1NH3 + 3O2 | 2N2 + 6H2O + 4Z1 |
| 4 | ☑ | Zeolite1 | 4Z1NH3 + 4NO + O2 | 4N2 + 6H2O + 4Z1 |
| 5 | ☑ | Zeolite1 | NO + 0.5O2 | NO2 |
| 6 | ☑ | Zeolite1 | 4Z1NH3 + 2NO + 2NO2 | 4N2 + 6H2O + 4Z1 |
| 7 | ☑ | Zeolite1 | 8Z1NH3 + 6NO2 | 7N2 + 12H2O + 8Z1 |
| 8 | ☑ | Zeolite2 | Z2 + NH3 | Z2NH3 |
| 9 | ☑ | Zeolite2 | Z2NH3 | Z2 + NH3 |
| 10 | ☑ | Zeolite2 | 4Z2NH3 + 3O2 | 2N2 + 6H2O + 4Z2 |
| 11 | ☑ | Zeolite2 | 4Z2NH3 + 4NO + O2 | 4N2 + 6H2O + 4Z2 |
| 12 | ☑ | Zeolite2 | 4Z2NH3 + 2NO + 2NO2 | 4N2 + 6H2O + 4Z2 |
| 13 | ☑ | Zeolite2 | 8Z2NH3 + 6NO2 | 7N2 + 12H2O + 8Z2 |
| 14 | ☑ | Pt | 2NH3+1.5O2 | N2+3H2O |
| 15 | ☑ | Pt | 2NH3+2.5O2 | 2NO+3H2O |
| 16 | ☑ | Pt | 2NH3+2NO+1.5O2 | 2N2O+3H2O |
| 17 | ☑ | Pt | NO + 0.5O2 | NO2 |
| 18 | ☑ | Pt | 2NH3 + 2NO2 | N2 + N2O + 3H2O |
| 19 | ☐ | | | |

Main | Solver Options | Site Elements | Coverages A(i) | Reactions

# 双活化层反应器模拟

不同的表面活化位被定义为催化剂层1 和催化剂层2

采用Turnover Number reaction rate units, 这样反应速率就与表面活化位相关联



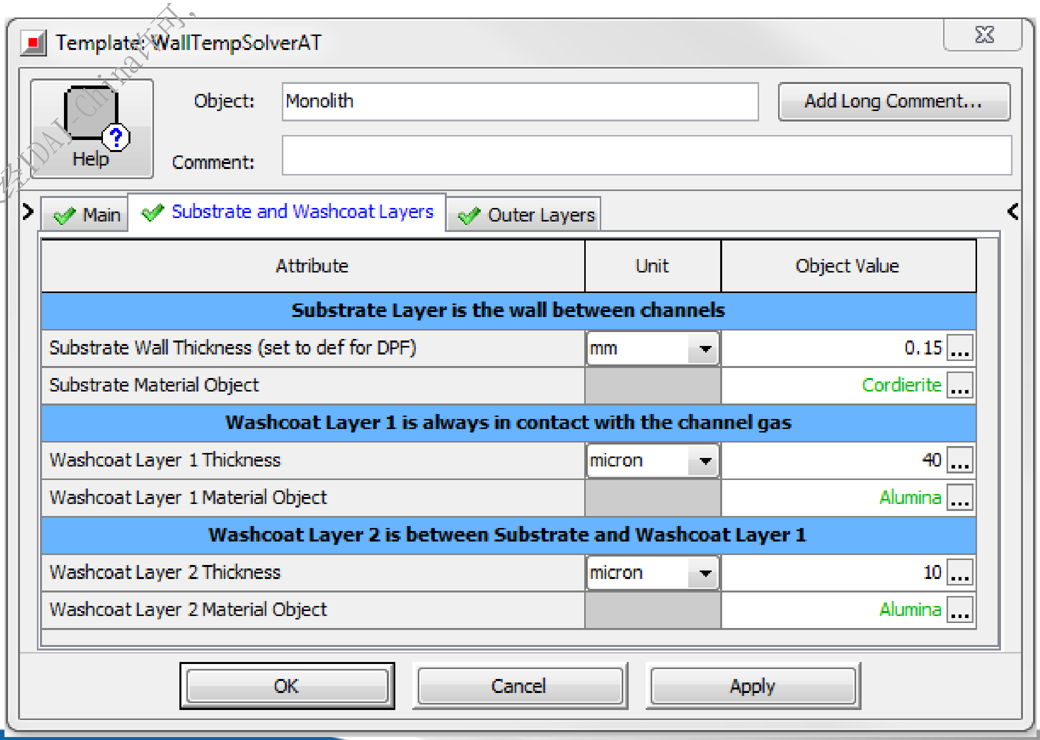

| Attribute | Unit | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Site Element Name | | Zeolite1 ... | Zeolite2 ... | Pt ... | ... |
| Site Density Option #1 | | | | | |
| Active Site Density | mol/m^3 | 115 ... | 25 ... | ign ... | ... |
| Site Density Option #2 | | | | | |
| Loading of Site Element | g/ft^3 | ign ... | ign ... | 10 ... | ... |
| Atomic Weight (g/mol) | | ign ... | ign ... | 195 ... | ... |
| Dispersion Factor | | ign ... | ign ... | 0.15 ... | ... |
| 2nd Layer Location | | ☐ | ☐ | ☑ | ☐ |

# 双活化层反应器模拟

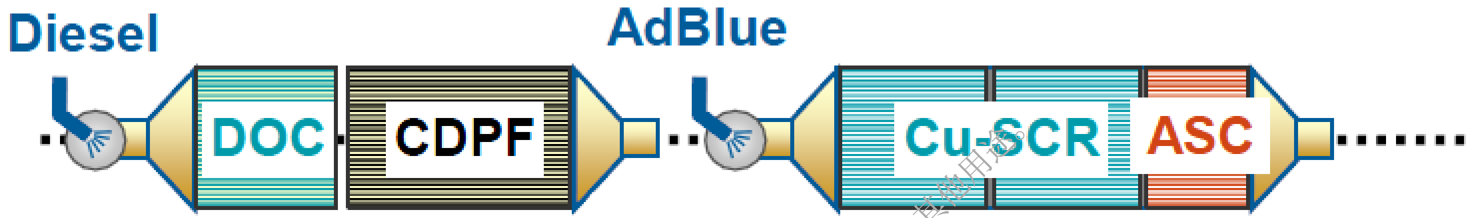
两个催化剂层都需要在WallTempSolverAT中定义
- Washcoat layer 1 与通道内的气体接触
- Washcoat layer 2 与载体层接触

孔隙扩散模型需要激活

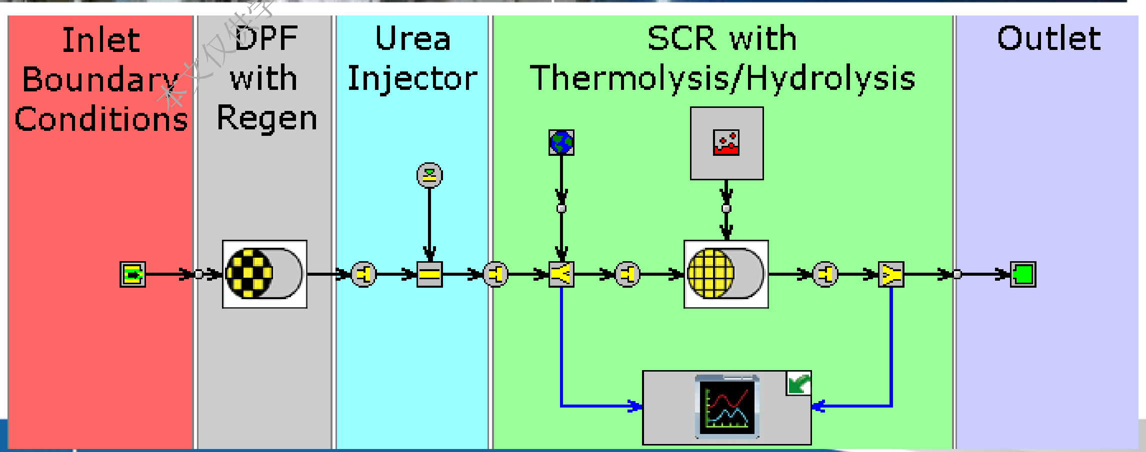


# GT提供完整的系统模拟解决方案







# 先进的CDPF工程应用方法介绍

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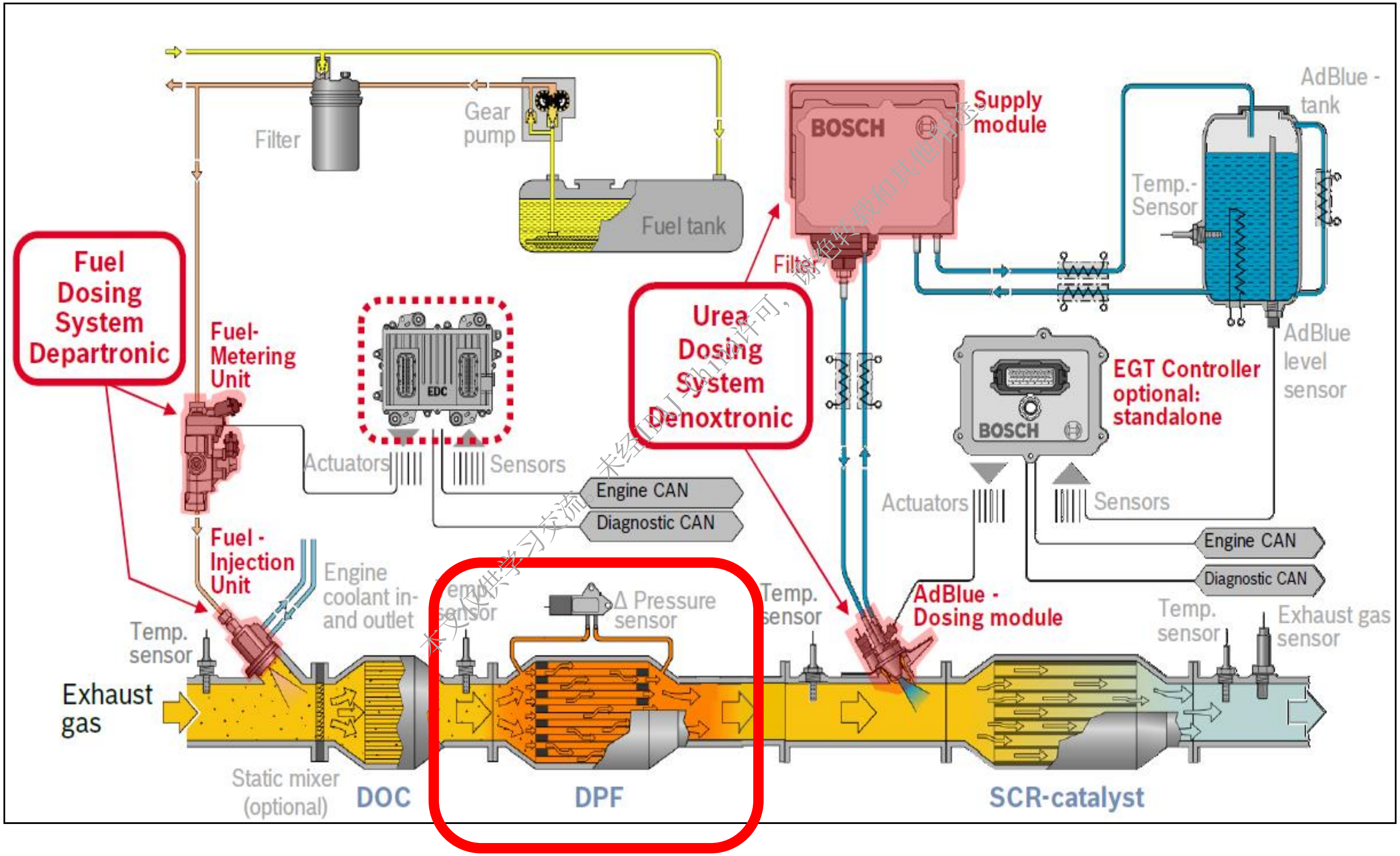


# 模型简介

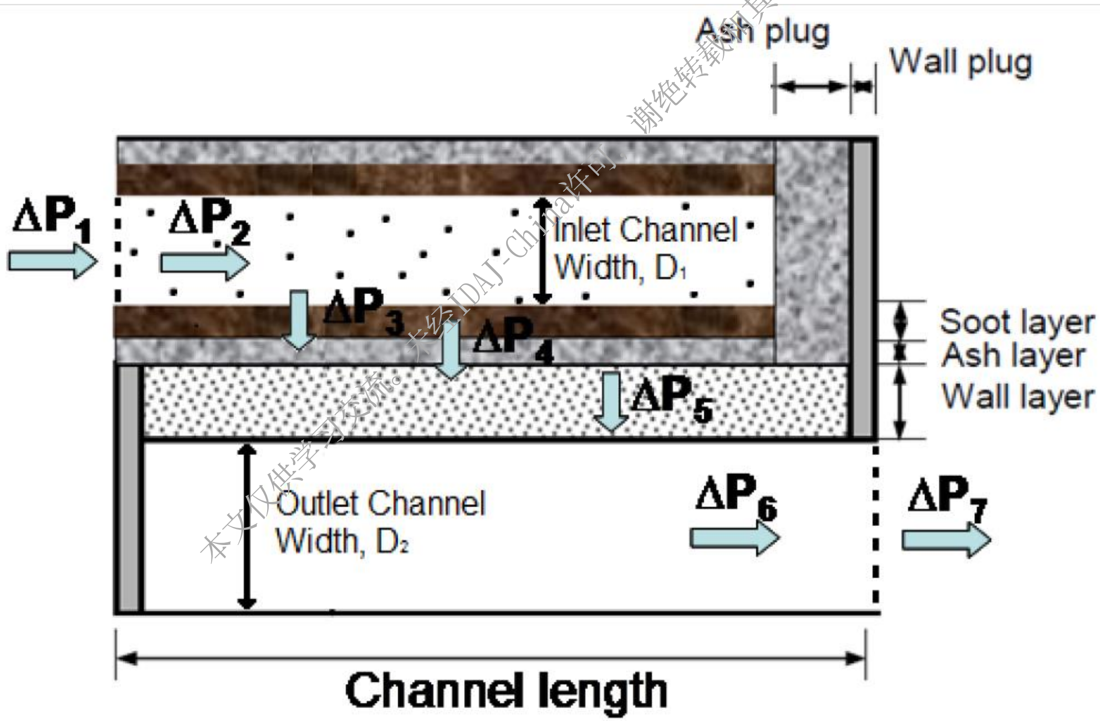
DPF模拟包括新鲜态下的压降模拟、soot累积模拟、完整的再生模拟（主动再生和被动再生）同时包含灰分模型，模拟CDPF由于老化引起的效率下降问题。

| | | | | |
|---|---|---|---|---|
| $C + NO_2$ | $\rightarrow$ | $CO + NO$ | $T > 200°C$ | (1) |
| $C + O_2$ | $\rightarrow$ | $CO + \frac{1}{2} O_2$ | $T > 450°C$ | (2) |
| $NO + \frac{1}{2} O_2$ | $\leftrightarrow$ | $NO_2$ | | (3) |

# 压差模拟模型

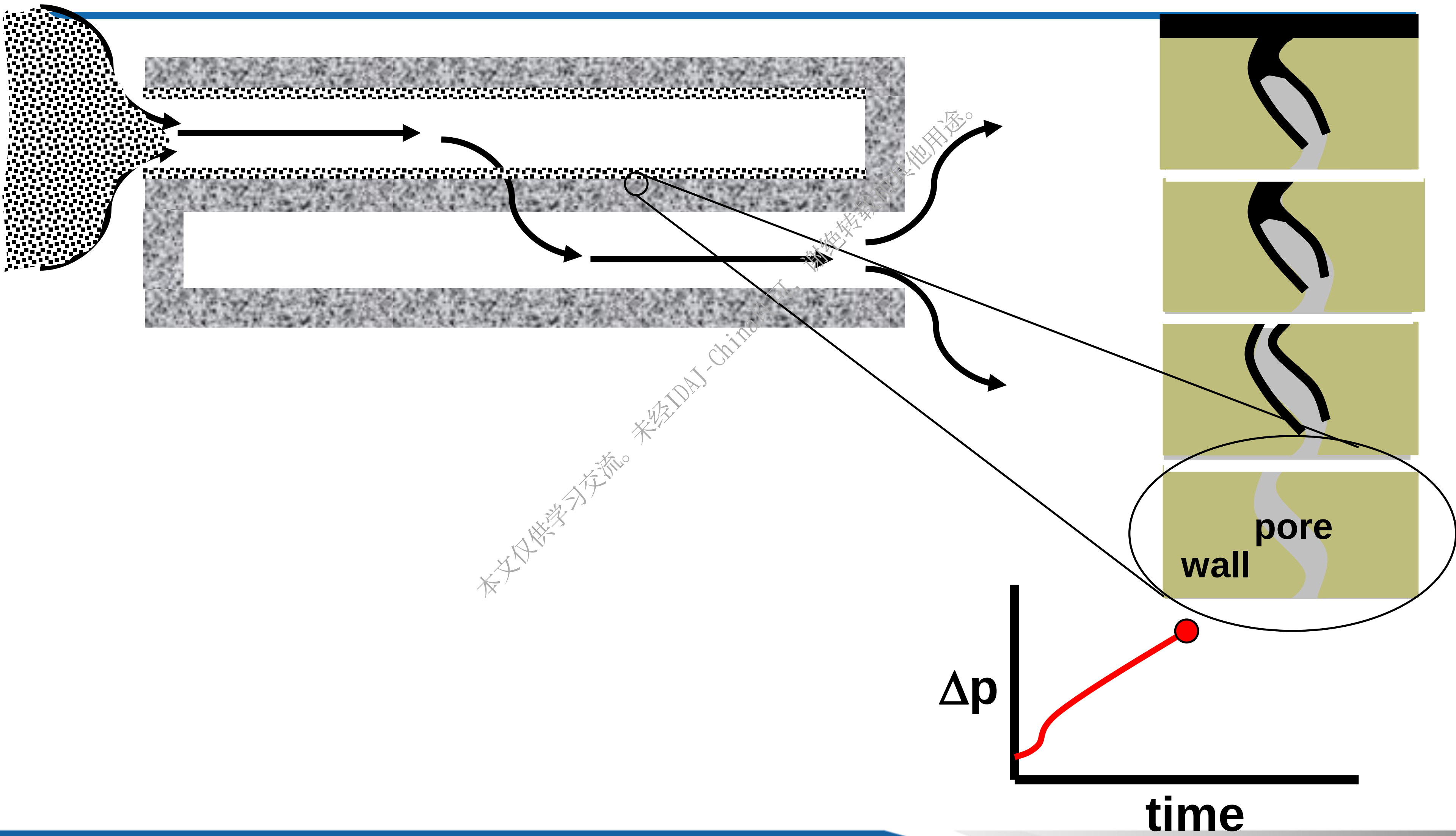
准确的压差与碳载量模型是柴油机后处理DPF-ECU标定控制中一个非常重要的环节，GT可以准确的模拟来为标定提供输入。



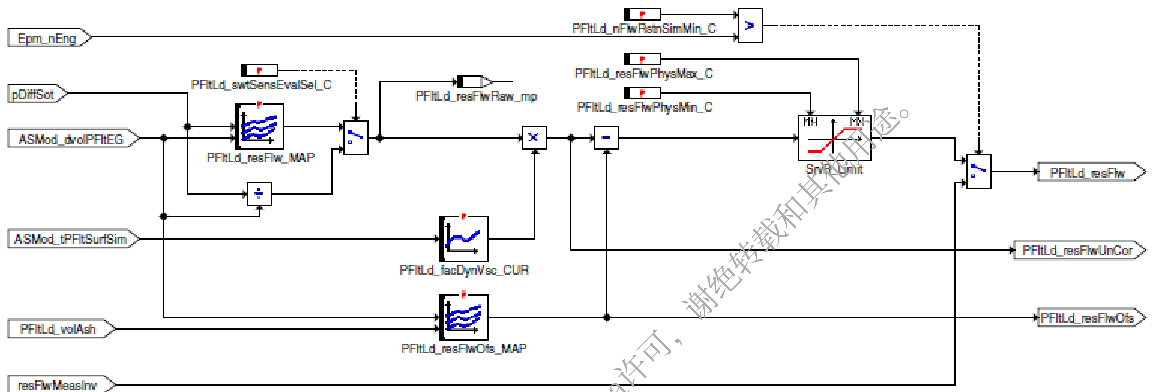


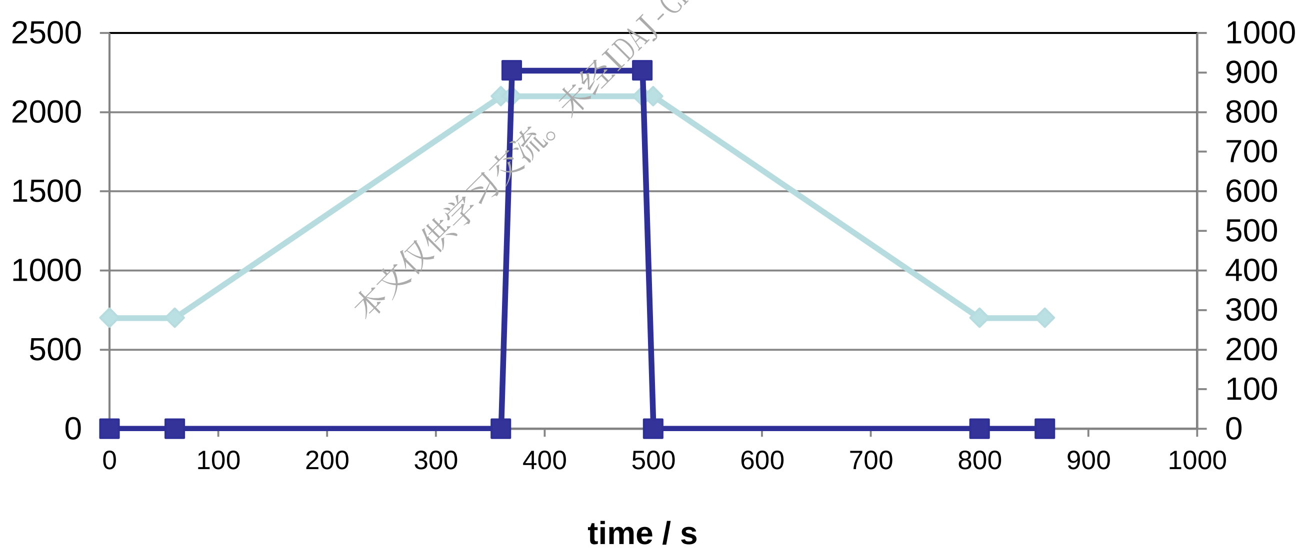

考虑碳颗粒堆积层和灰分层对压差的影响

# DPF过滤和soot_loading过程简介



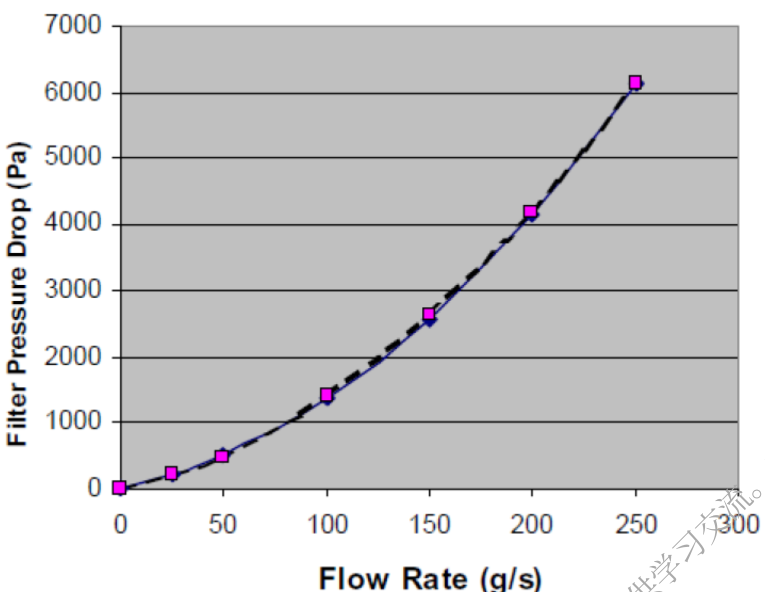
# BOSCH控制策略DPF流阻计算模块



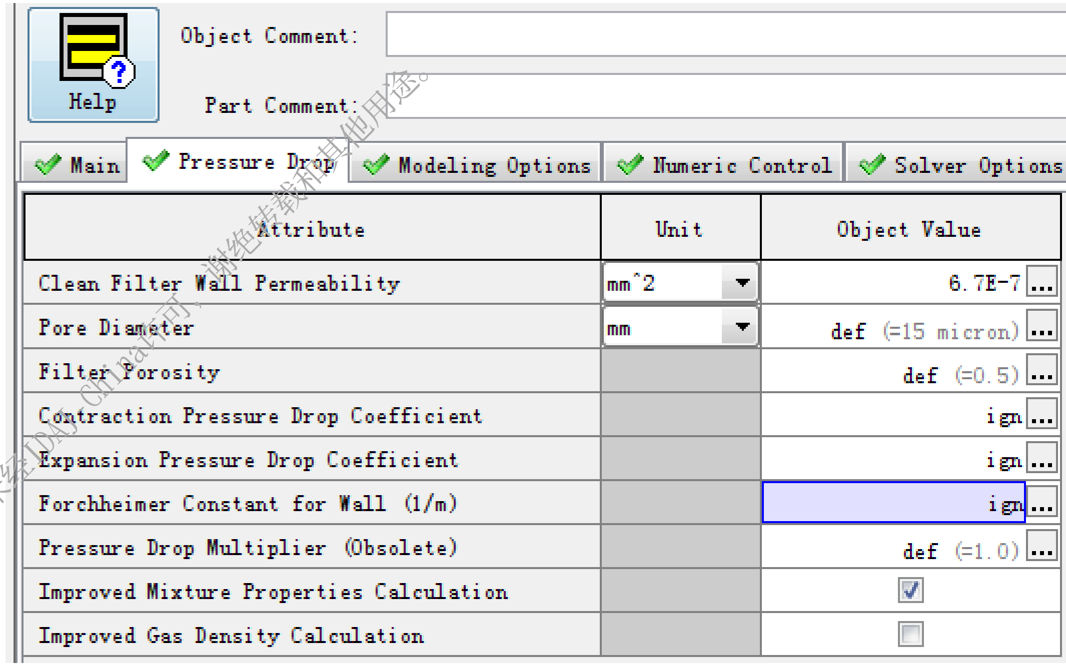




DPF压差流量台架试验方法

# 新鲜DPF的压降标定



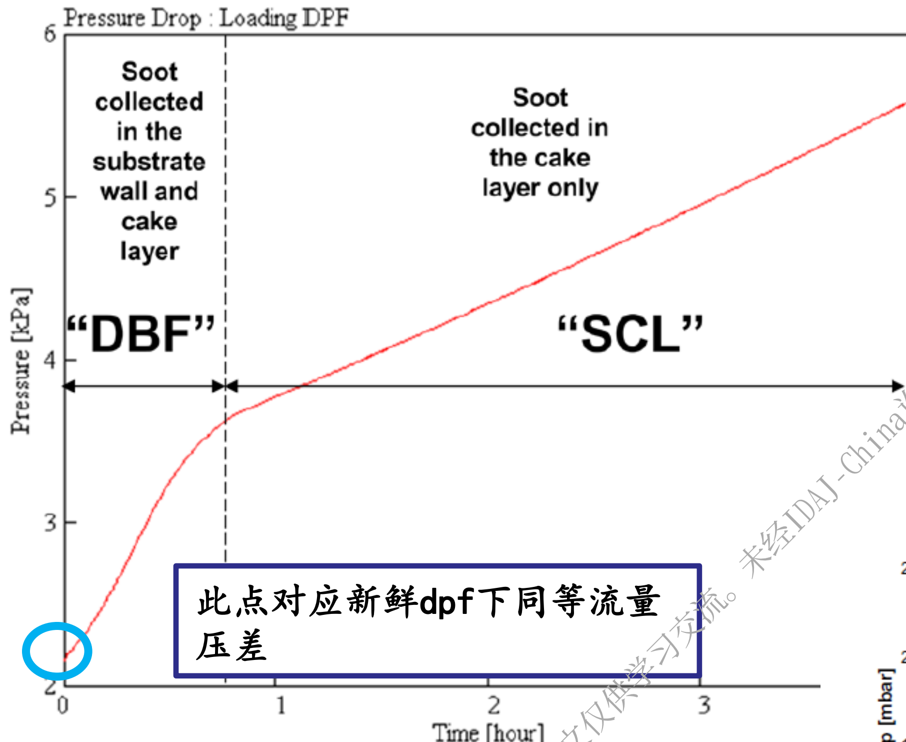

没有soot的情况下压差流量测试



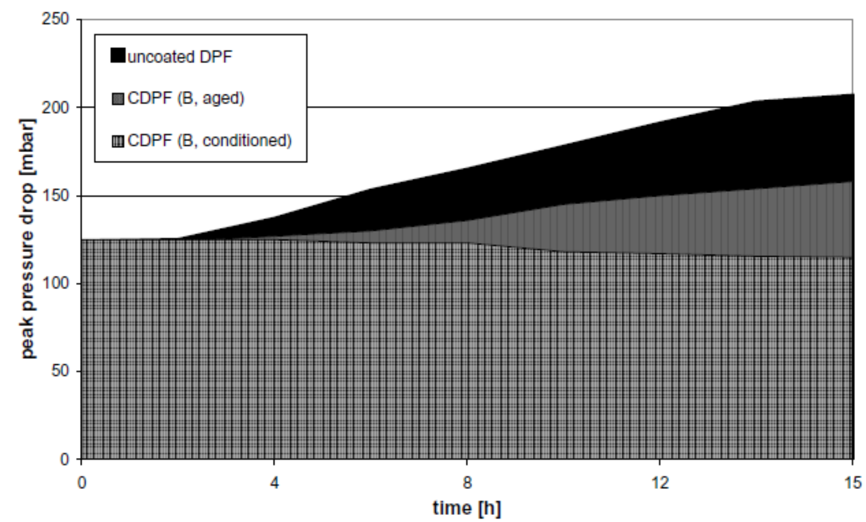



**IDAJ 可以提供试验方法建议以及标定方法：**
**通过标定3个系数来模拟在进出口的膨胀收缩和壁流式dpf流动引起的压力损失。**
**对DPF碳累积开始状态下的压降进行准确模拟**

# DPF soot 堆积模型



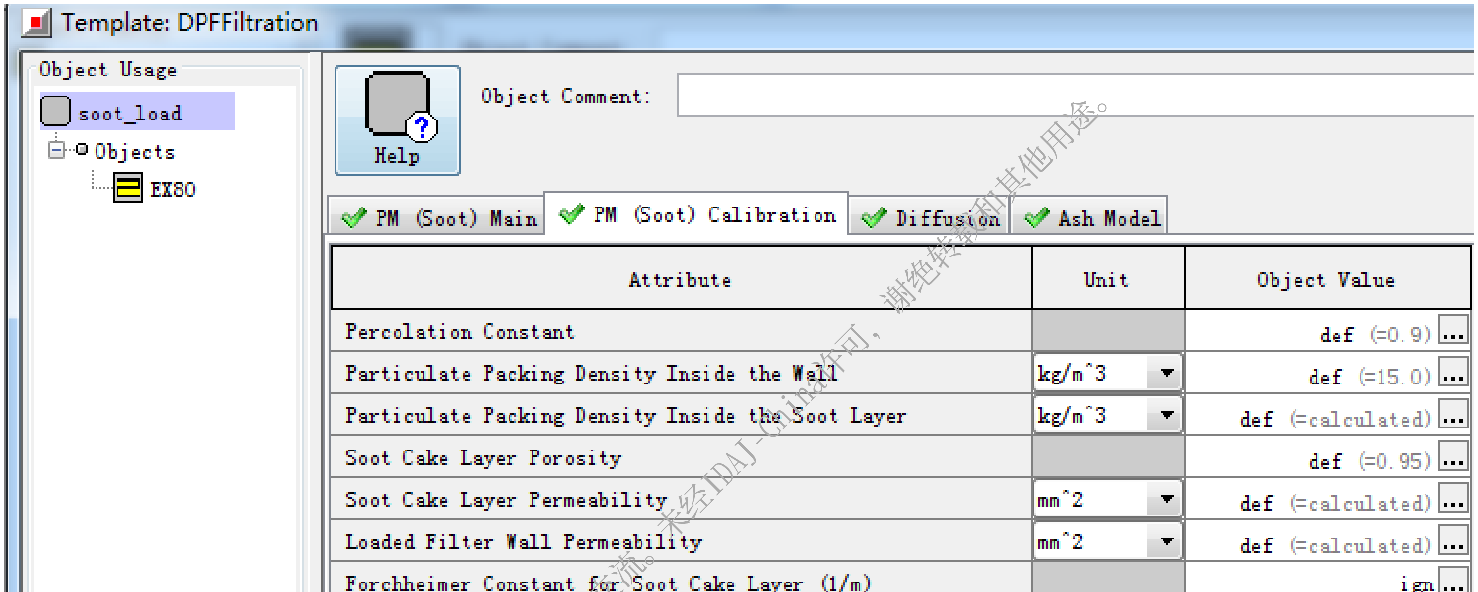

Umicore试验






IDAJ 可以提供标定培训与支持

# DPF-soot累积模型



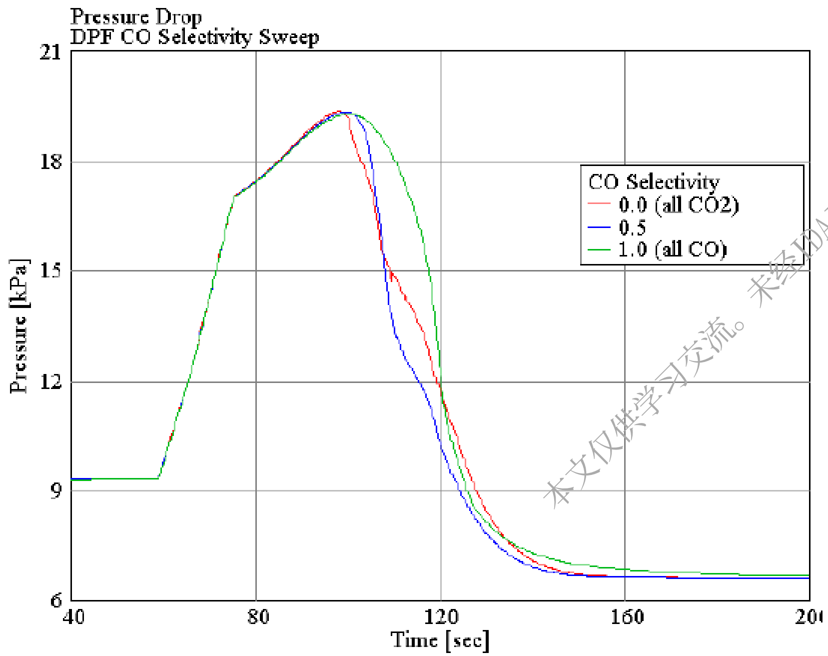

- 通过标定几个因子，来模拟压差对碳积累的时间变化，如果是CDPF建议在无被动再生的情况下进行试验，以免发生碳一边累积一边消耗。
- 例如下图soot累积工况

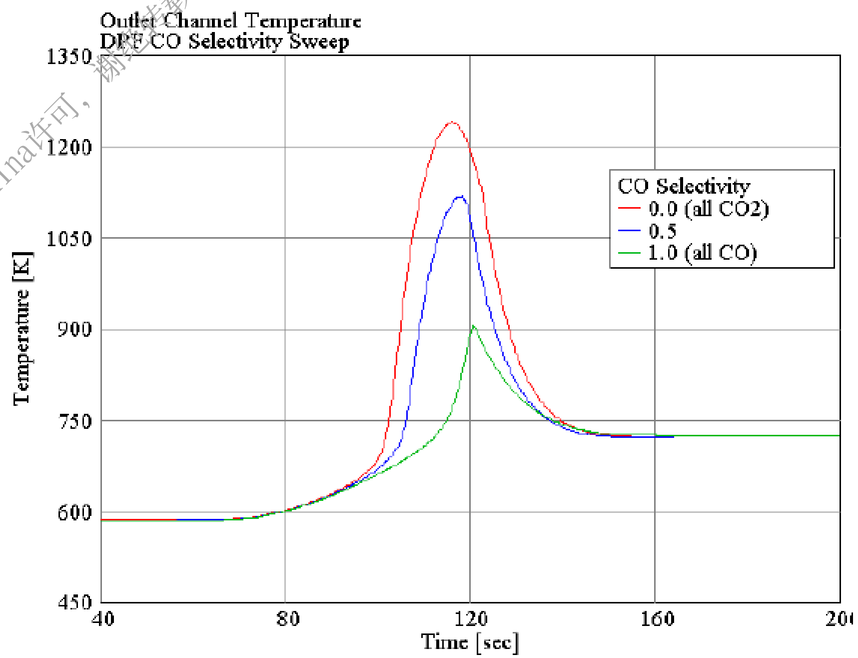
| Aging Mode | Engine Speed | Torque | System Inlet Temperature | Time | Comment |
|---|---|---|---|---|---|
| Soot accumulation | 2200 rpm | 145 Nm | 230-240°C | 14.5 h | 50–70 g soot / filter |

# DPF Regeneration

•GT可以模拟详细的被动再生和主动再生（CDPF），可以模拟HC起燃后温度上升和压力下降的过程，同时能够模拟DTI等恶劣工况
•GT可以模拟CDPF由于热冲击等引起的催化剂老化-NO2形成效率下降以及soot转化效率下降

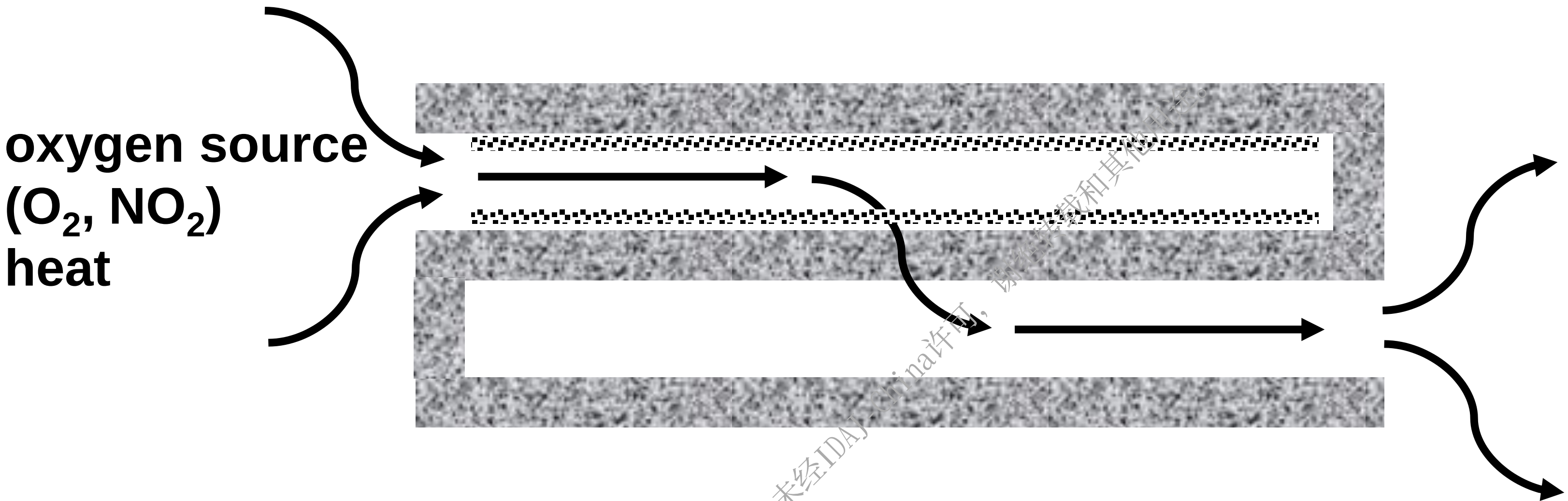


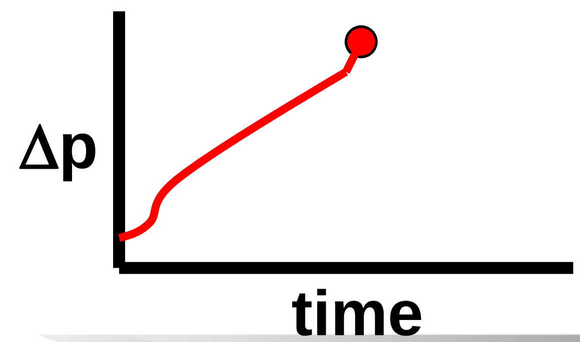


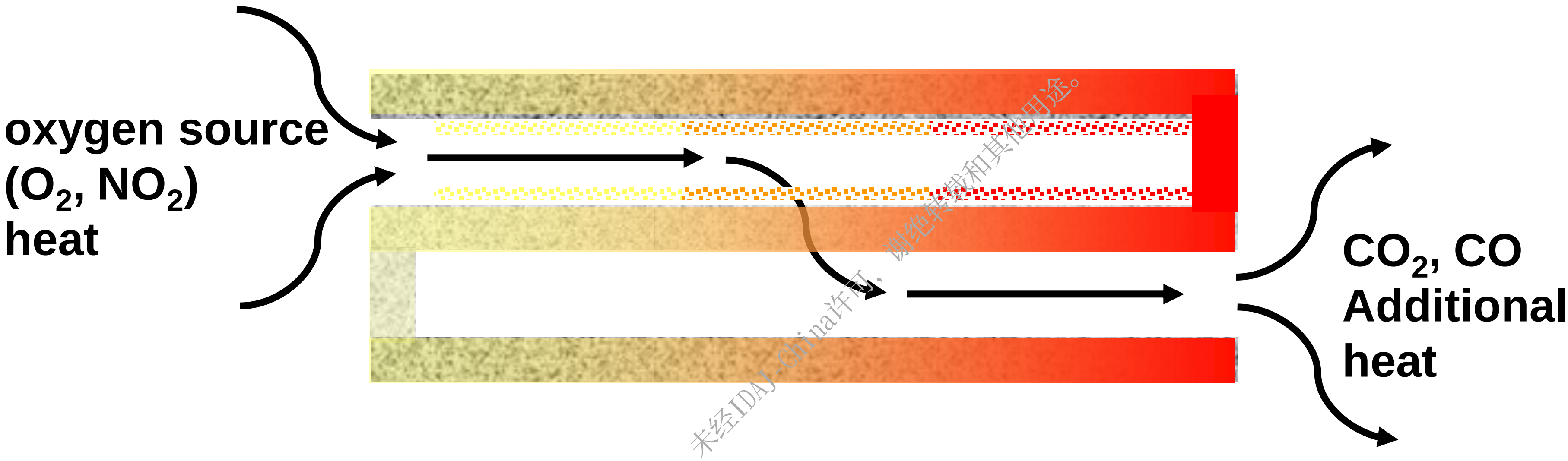

DPF再生过程中压差与温度的变化

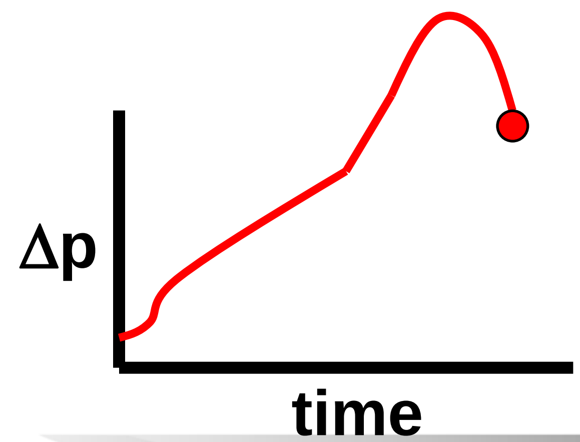
# Regeneration过程介绍



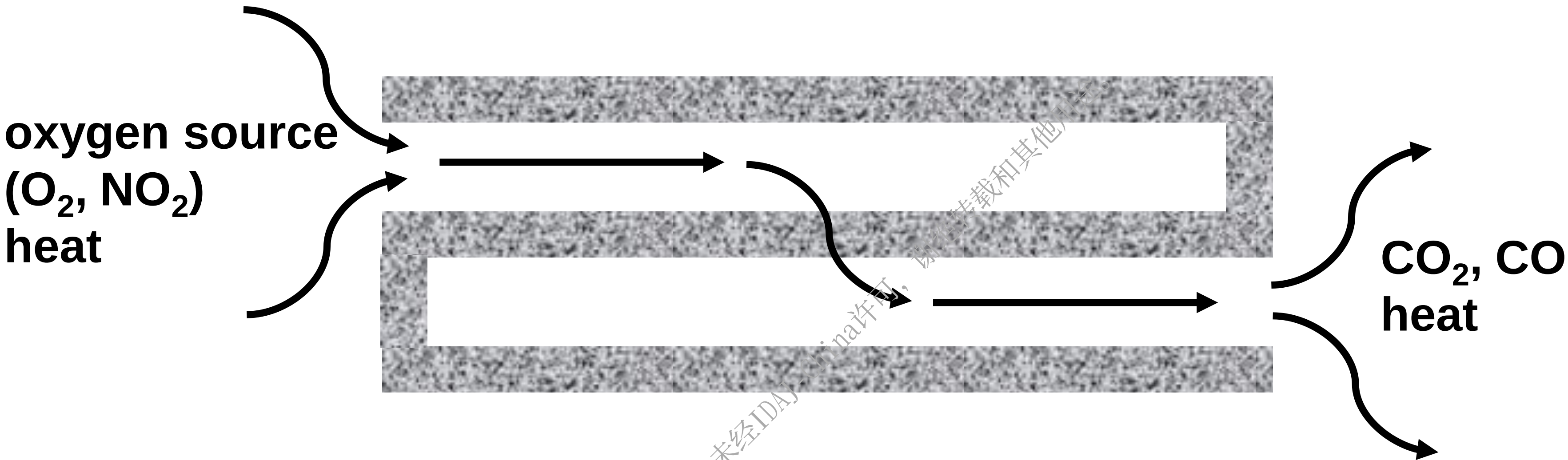



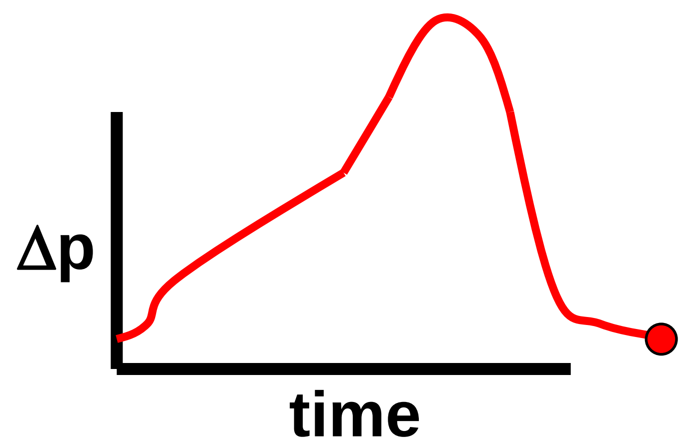
# Regeneration介绍



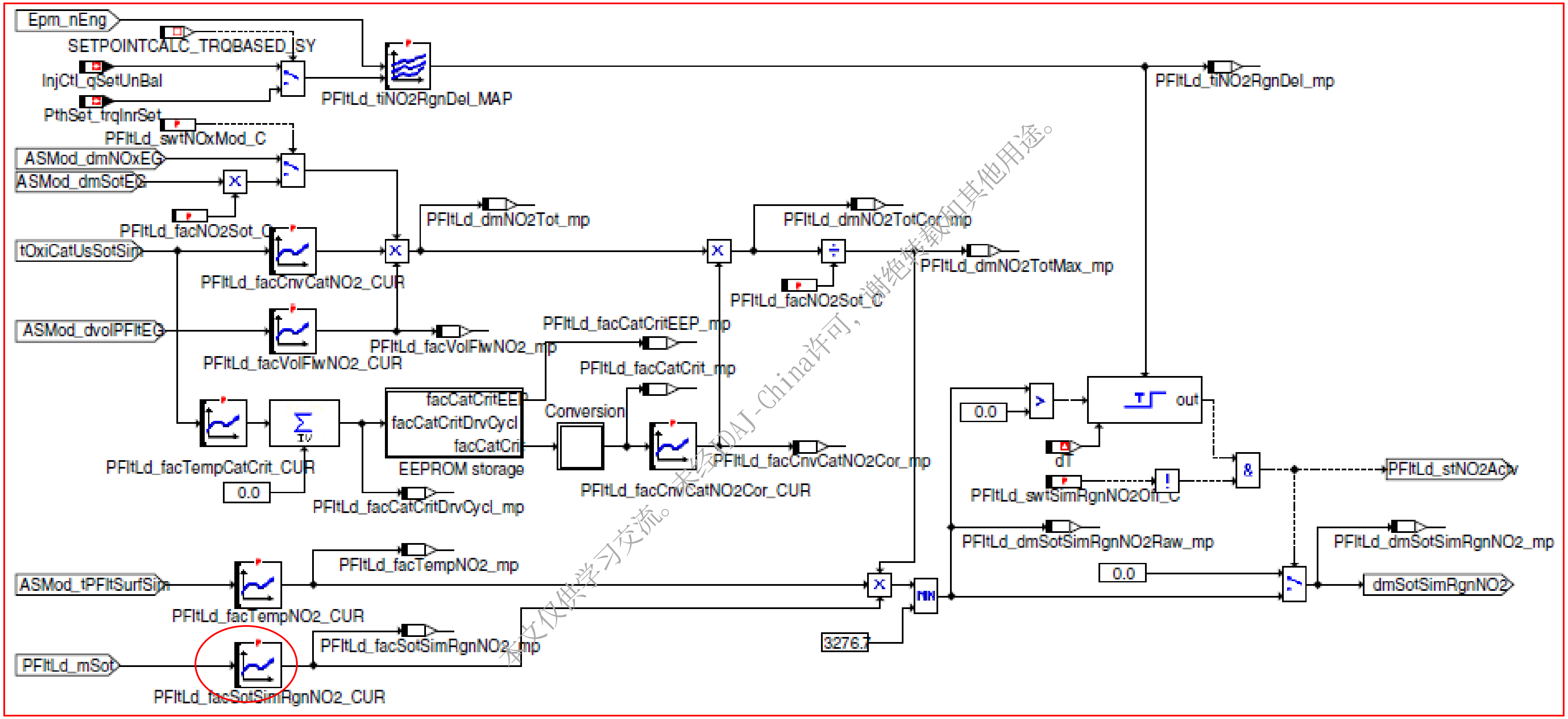



# Regeneration介绍



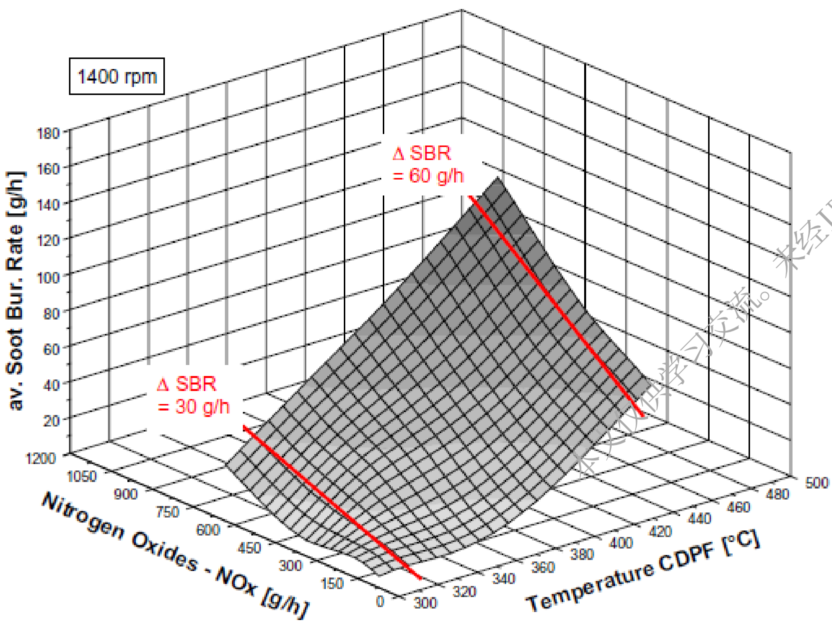
# BOSCH soot被动再生控制逻辑



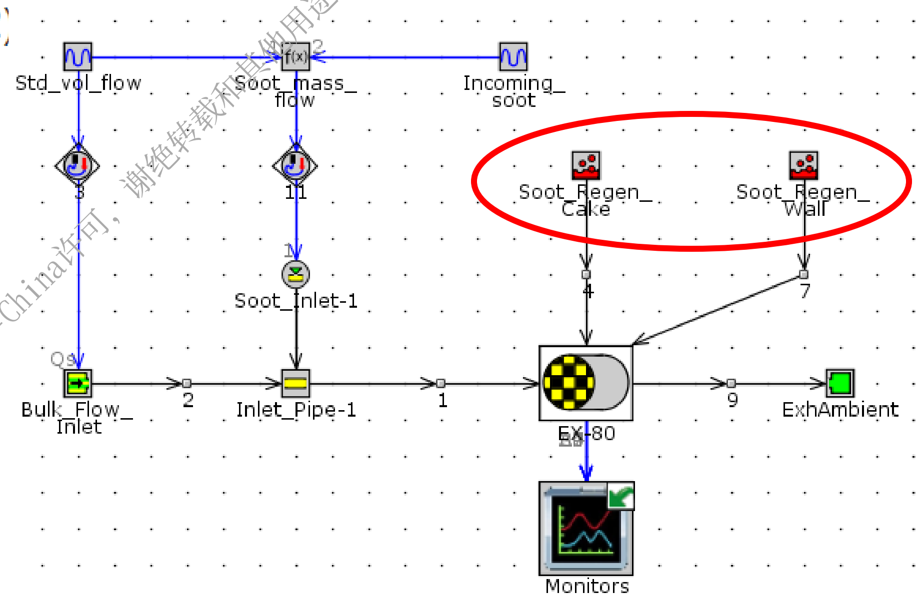
# DPF Regeneration 模拟

➢被动再生与主动再生结合

| | | | | |
|---|---|---|---|---|
| $C + NO_2$ | $\rightarrow$ | $CO + NO$ | $T > 200°C$ | (1) |
| $C + O_2$ | $\rightarrow$ | $CO + ½ O_2$ | $T > 450°C$ | (2) |

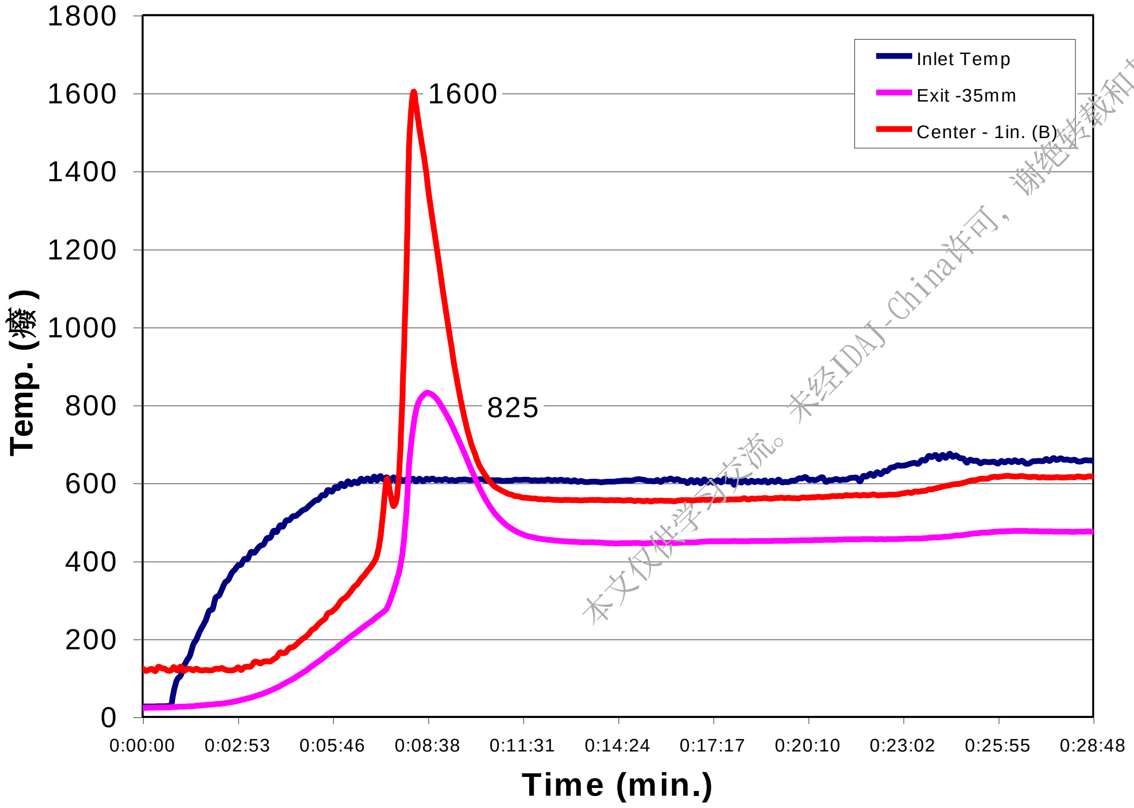



CDPF被动再生速率




输入发生的被动再生与主动再生反应，方便的进行不同Nox/C、不同温度下的被动再生与主动再生速率的模拟。

# 不可控的主动再生模拟-DTI

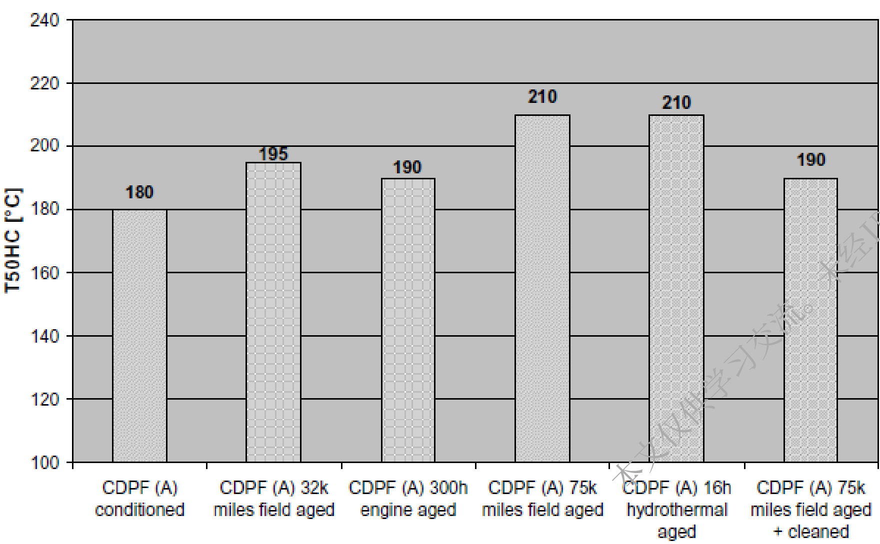




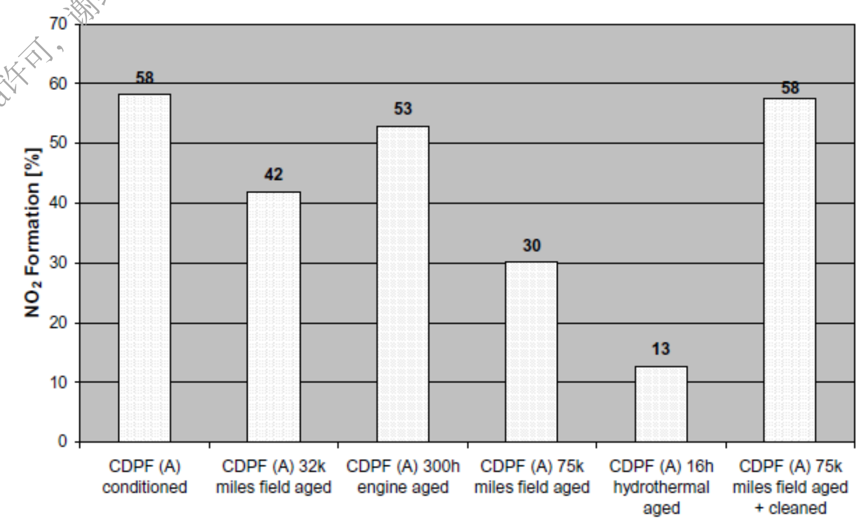

激活dpf中的组分扩散模型，考虑02等组分在不可控再生中的扩散现象。不可控再生中的高温会破坏载体和催化剂

# CDPF 老化模拟

DPF在使用过程中，由于热冲击引起的催化剂烧结以及铂族金属支撑剂的稳定性下降，以及灰分堆积都会引起催化剂性能的老化下降，在模拟中需要考虑.

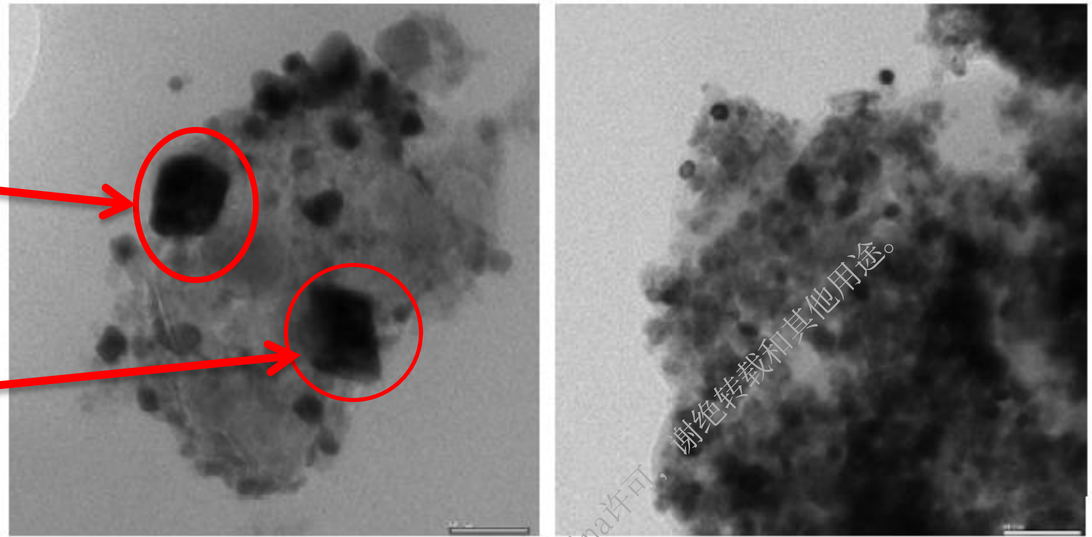



HC Light-Off of Aged CDPFs -T50 light-off temperatures

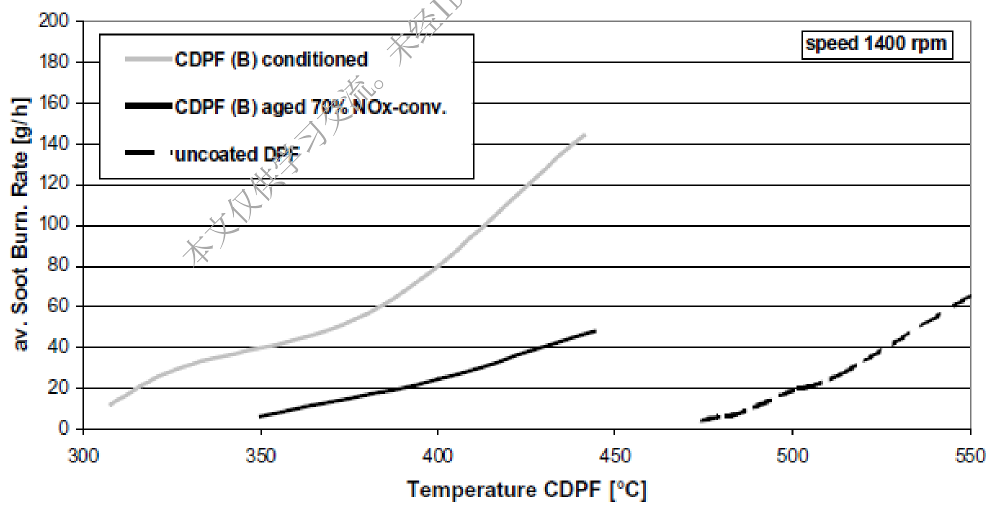



NO2 Formation Efficiency for Aged CDPFs

明显的催化剂烧结



老化后的催化剂电镜照片




不同老化状态下的soot反应速率

# GT老化模拟设置

**GT反应速率与活化位数目相关，通过改变活化位数目，可以体现出老化对反应的影响。**

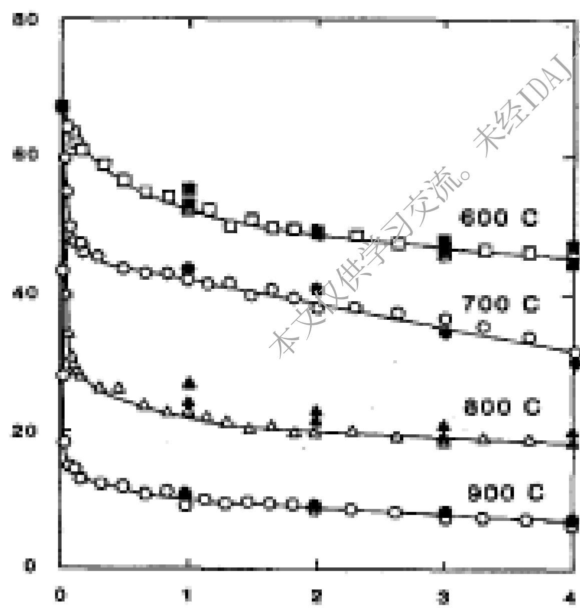
| | Attribute | Unit | Object Value |
|---|---|---|---|
| | Species Settings Object | | def ... |
| | Rate Expression Basis | | turnover number |
| | Concentration Specification | | mole\m3 |
| | Diffusion | | quasi-steady |
| ☐ | Pore Diffusion Object (AA Solver Only) | | ... |

Main | Solver Options | Site Elements | Coverages A(i) | Reactions

**Turnover number rate is moles reacted per moles of active sites per second**

$$\frac{mol_{reacted}}{mol_{active-sites}\cdot s}$$

Dispersion (%)




Aging Time (hours)

**Example from Fig. 6 in "A Study of Thermal Aging of Pt/Al2O3 Using Temperature-Programmed Desorption Spectroscopy", Beck, D., and Carr, C., 1987, Journal of Catalysis 110.**

Help

Object Comment: Base mechanism from Metkar

Part Comment:

Main | Solver Options | Site Elements | Coverag

| Attribute | Unit | 1 |
|---|---|---|
| Site Element Name | | Cu-CHA ... |
| Site Density Option #1 | | |
| Active Site Density | mol/m^3 | 360 ... |
| Site Density Option #2 | | |
| Loading of Site Element | g/ft^3 | ign ... |
| Atomic Weight (g/mol) | | ign ... |
| Dispersion Factor | | ign ... |
| 2nd Layer Location | | ☐ |

# 小结:

➢高排放的中重型发动机开发对主机厂是个严峻的挑战，发动机制造商不仅要关注整机性能，油耗等指标，还要满足排放的要求，对开发成本和周期是个挑战。
➢需要进行大量的发动机标定试验，进行缸内燃烧优化与缸外后处理优化标定的trade-off，需要在不同的技术路线之间做取舍，需要考虑产品销售地区的油品以及使用工况等条件
➢后处理开发标定将花费非常大的时间，此标定包括台架标定和整车标定验证以及OBD和排放一致性，再生周期以及保护等
➢排放后处理的耐久性要求
➢采用先进的仿真手段和模型能够在开发初期和后期改进中提供帮助，大大缩短开发周期与成本，GT软件可以提供完整的系统耦合仿真分析解决方案。
•最小化尾管的排放以满足汽车排放法规
•优化涂层，铂类金属负载量，催化器尺寸，降低成本等
•满足封装和压降要求
•最大化利用热能缩短起燃（light-off）时间-瞬态温度模拟，以及组分转化效率最大-例如加快WHTC 冷态
•在极限温度下保护部件-DTI等
•确定最优布置配置-后处理布置位置以及顺序
最佳布局设计:
DOC+DPF+SCR, DOC+SCR+DPF, etc
Close-coupled cat, pre-turbine cat
•发动机预标定-提供预标定map
控制策略开发:
•再生频率，尿素喷射率，稀/浓燃循环

# 谢谢大家！