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Numerical analysis on a novel CGPFs for improve NO_x conversion efficiency and particulate combustion efficiency to reduce exhaust pollutant emission

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Abstract: Improving the NO_x conversion efficiency and particulate combustion efficiency under cold start conditions (low temperature conditions) is still the main challenge faced by catalytic gasoline particulate filter system (CGPFs). In this study, the physical and mathematical models of novel CGPFs are proposed based on the computational fluid dynamics software. Then, the models are validated based on experiments, and the performances of conventional and novel CGPFs are analyzed comparatively. The comparison conclusions indicate that the NO_x conversion efficiency of the novel CGPFs increases by 3.2% and the particulate combustion efficiency increases by 2.7% under the same operating condition. Finally, the effects of exhaust flow v_f , exhaust oxygen concentration C_o , exhaust NO concentration C_{NO} and electric heating power P_e on the NO_x conversion efficiency and particulate combustion efficiency are investigated. The weights of each influencing parameter on the NO_x conversion efficiency and particulate combustion efficiency are explored by orthogonal tests. The conclusions show that the NO_x conversion efficiency is increased

22 by 3.6% and the particulate combustion efficiency is increased by 16.7% compared to the initial
23 condition. This study has an important reference value for improving the purification efficiency of
24 vehicle emission under cold start conditions.

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26 **Keywords:** Particulate combustion efficiency; Electric heating power; Catalytic gasoline particulate
27 filter system; Gasoline engine; NO_x conversion efficiency; Vehicle emission.

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Nomenclature		T_1	the target exhaust gas temperature, K;
		P	the heating power, kW;
ρ	the density of exhaust gas, kg/m ³ ;	E_1	heat transfer coefficient, 1.2~1.3;
$\vec{u}$	the flow velocity of exhaust, m/s;	C_e	exhaust specific heat capacity,
w_s	formation efficiency of component s ;	Q_e	flow rate, kg/h;
u_x	velocity components in X direction, m/s;	T_0	initial temperature, K;
u_y	velocity components in Y direction, m/s;	t	unit time, h
u_z	velocity components in Z direction, m/s;	K_s	the component s reaction rate, mol/(L·s);
p	pressure, Pa;	A	apparent activation energy, J/mol;
μ	dynamic viscosity, Pa·s;	B	temperature index;
F_x	mass forces acting on the microelement in X direction, N;	E_a	the activation energy, J/mol;
F_y	mass forces acting on the microelement in Y direction, N;	R_0	the gas constant; $R_0=8.314$ J/(mol·K).
F_z	mass forces acting on the microelement in Z direction, N;	$NO_{m,in}$	mass fraction of NO in inlet, ppm;
Y_s	the exhaust component s mass percentage, %;	$NO_{m,out}$	mass fraction of NO in outlet, ppm;
D_s	component s effective mass diffusivity, m ² /s;	$S_{m,in}$	mass concentration of particulate in inlet, %;
T	exhaust temperature, K;	$S_{m,out}$	mass concentration of particulate in outlet, %;

43 1. Introduction

44 The amount of particulate emissions from gasoline vehicles has already attracted worldwide
45 attention as the number of gasoline vehicles increases rapidly (Wang et al. 2018; Sthel et al. 2019).
46 Increasing the number of particulate emissions will not only seriously endanger human health, but
47 also lead to the formation of disastrous weather (Qian et al. 2019; Dai et al. 2019). Nowadays,
48 although homogeneous mixing technology (Xu et al. 2020) and laminar oxidation technology
49 (Zhong et al. 2016; Distaso et al. 2019) have been successfully applied to gasoline vehicles, the
50 particulate emission of the gasoline vehicles still can not meet the increasingly stringent emission
51 standards (Jain et al. 2017; Chen et al. 2017). Therefore, reducing the particulate emission of
52 gasoline vehicles has become an urgent problem to be solved (Wang et al. 2020). Catalytic gasoline
53 particulate filter system (CGPFs) is currently regarded as one of the most useful automotive exhaust
54 post-treatment technologies (Zuo et al. 2021; Du et al. 2015). As shown in **Fig.1**, the post-treatment
55 system of the gasoline engine comprises a catalytic converter and a particulate filter (Zhong et al.
56 2021; Jiang et al. 2017). First, the exhaust gas generated during the vehicle load process enters the
57 catalytic converter (Zhang et al. 2016). When the catalytic converter is working, the HC and CO of
58 the exhaust gas are purified, and NO is converted into NO₂ (Bermudez et al. 2015; E et al. 2020).
59 Then, the exhaust gas with sufficient NO₂ concentration flows into the particulate filter (Chen et al.
60 2014). In the particulate filter, the particles react with NO₂ to generate clean exhaust gas (Caliskan
61 et al. 2017; E et al. 2016). Finally, the clean exhaust gas flows into the atmosphere from the outlet
62 of the CGPFs.

Fig. 1. The conventional model structure of catalytic gasoline particulate filter system.

Therefore, in order to improve the emission control effect of gasoline vehicle exhaust pollutants, the relevant property should be investigated. In the study of particulate filters, many scholars have extensively studied the regeneration characteristics of them. Zhang et al. (2018) developed a one-dimensional full-scale diesel particulate filter (DPF) model to investigate the effect of ash deposition on DPF fuel loss. The results indicated that ash caused 0.02% to 0.42% fuel loss; regular ash cleaning saved 0.22% to 0.69% of fuel consumption. Jiao et al. (2017) established the reaction mechanism between NO_x and PM in DPF, and explored the reaction process of NO_x and PM under different inlet conditions. The results showed that when the NO₂ in the inlet exhaust accounted for 0.7~0.8 of the total NO_x content, particulate had a good regeneration effect; when the molar ratio of NO_x to PM in the inlet exhaust was greater than 8, particulate could be completely passively regenerated. Fang et al. (2019) optimized the regeneration property of DPF under 2.5g/L and 5g/L particulate loadings according to an experimental method. It was found that the optimal regeneration temperature was 550 °C with a flow rate of 16.8 g/s for a 2.5 g/L particulate load, and the optimal regeneration temperature was 550 °C with a flow rate of 19.6 g/s for a 5 g/L particulate load. Choi et al. (2014) compared the pressure drop characteristics of two particulate filters with different porosity based on a visualized experimental method. It was shown that the filter with higher porosity had lower pressure drop and regeneration efficiency for the same particulate load.

82 Ko et al. (2019) analyzed the particle number (PN) emission characteristics of GDI vehicles with
83 and without gasoline particulate filter (GPF) under cold-start conditions. The results showed that the
84 PN emissions of GDI vehicles with GPF were significantly reduced at higher engine speed
85 conditions. Bock et al. (2020) investigated the ability of catalytic GPF to treat dicarboxylic acids in
86 ethanol-blended gasoline emissions according to an experimental method. It was found that the
87 catalytic GPF was able to remove 80% to 92% of the dicarboxylic acids from the engine exhaust. E
88 et al. (2020) made a discussion on the effects of various factors on the particulate oxidation property
89 of DPF. They concluded that the particulate oxidation property could be enhanced as the exhaust
90 temperature was 600-750 K, the particulate concentration was 0.06-0.08, and the microwave
91 heating power was 800-1200 W.

92 In the study of catalytic converters, Mianzarasvvand et al. (2017) researched the effects of
93 electric heating temperatures and heating times on catalytic converters. They found that the heating
94 temperature was at least 450°C, and the heater was required to start 35 s in advance. Broatch et al.
95 (2008) made an in-depth analysis of the intake air heating technology of catalytic converters. They
96 claimed that compared with the electric plug, the intake heating technology can reduce HC
97 emissions by 13%, CO emissions by 5%, and NO emissions by 3%. Horng et al. (2004) investigated
98 the effects of heating energy and CO content of catalytic converter on CO conversion rate. The
99 results revealed that the CO conversion efficiency was improved when the heater was located at the
100 inlet. Vaishnav et al. (2014) explored catalytic converters with diffuser devices at the inlet and
101 demonstrated that the structure optimized the exhaust flow route and improved the purification
102 effect. Day et al. (2020) surveyed various catalysts in catalytic converters, revealed that compared

103 with noble metal catalysts, Cu was the most powerful and active catalyst for CO. Ibrahim et al.
104 (2018) proposed that insulating material was placed in the carrier channel to investigated the
105 distribution of the internal flow field and the change of heat diffusion. They found that the gas
106 uniformity and thermal properties were improved by 5% and 18%, respectively.

107 In conclusion, it is found that the current researches on CGPFs focused primarily on various
108 influence factors such as structural parameters, intake parameters, and different regeneration
109 technologies on the individual catalytic converter and particulate filter interior flow field, pressure
110 drop, and regeneration rate. A comprehensive in-depth investigation of the NO_x conversion
111 efficiency and particulate combustion efficiency of CGPFs is relatively lacking. It can be found
112 through researches (Mu et al. 2019) that improving the uniformity of engine exhaust gas flow in
113 catalytic converters significantly increases the property and lifetime of catalytic converters. In the
114 aspect of active regeneration of particulate filters for low exhaust temperature conditions, there are
115 many researches on the use of microwave heating technology, but there is a lack of research on the
116 use of electric heating technology. Zhong et al (2019) investigated the effect of electrically heated
117 regeneration techniques on the regeneration property of particulate filter at different temperatures
118 but did not study the effect law of electric heating regeneration techniques concerning the CGPFs
119 NO_x conversion efficiency and particulate combustion efficiency.

120 Therefore, to enhance the NO_x conversion efficiency and particulate combustion efficiency at
121 low exhaust temperature conditions, the physical and mathematical models of a novel CGPFs are
122 proposed based on the computational fluid dynamics software. The properties of conventional and
123 novel CGPFs are analyzed comparatively, and the computational models are validated according to

124 experiments. Finally, the influences of flow rate, NO concentration, oxygen concentration, and
125 heating power on the regeneration property of the novel CGPFs are investigated. The weights of
126 each influencing parameter on the NO_x conversion efficiency and particulate combustion efficiency
127 are explored by orthogonal tests, and the novel CGPFs is also preferentially selected under
128 simulated working conditions. This work will provide a theoretical basis for further enhancing the
129 purification efficiency of vehicle emission under cold start conditions.

130 **2. The novel CGPFs model construction**

131 **2.1 Physical model**

132 The geometry of the novel CGPFs is shown schematically in **Fig 2**. It is mainly made up of
133 eight parts, which are inlet tube region, expansion tube region, outer carrier region, inner carrier
134 region, air gap region, filter region, shrink tube region, and outlet tube region. The structural
135 parameters of the novel CGPFs are shown in **Table 1**.

136 The process of exhaust gas purification in the novel CGPFs are as follows:

- 137 (a) The gasoline engine exhaust gas in low temperature operation flows from the inlet tube into the
138 expansion tube region and is heated by the electric heating equipment in the expansion tube region.
- 139 (b) The heated exhaust gas undergoes a catalytic reaction in both carrier regions, where the main
140 pollutants of the exhaust gas are purified and NO_x is converted to NO₂.
- 141 (c) The particulate in the exhaust is trapped by the filter and oxidized by NO₂ in the filter region, so
142 as to remove the particulate and achieving the objective of purifying the exhaust gas.
- 143 (d) The purified gasoline engine exhaust gases are discharged from the shrink tube region and outlet
144 tube region.

Fig. 2. The geometry of the novel CGPFs.

Table 1 The structural parameters.

Structures	Inlet pipe	Expansion pipe	Outer carrier	Inner carrier	Air gap	Filter	Shrink pipe	Outlet pipe
Length(mm)	25	25	100	100	25	100	25	25
Diameter(mm)	47	/	100	50	100	100	/	47

Table 2 shows the carriers and filter related structural parameters.

Table 2 The carrier and filter related structural parameters.

Structures	Material	Pore density (cps)	Wall thickness (mm)	Channel diameter (mm)	Porosity (%)
Outer carrier	Cordierite	400	1.10	0.17	75
Inner carrier	Cordierite	500	0.97	0.17	72
Filter	SiC	325	1.01	0.40	51

2.2 Mathematical model of the CGPFs

The numerical computational models for the novel CGPFs are developed by making the

152 following reasonable assumptions (Pan et al. 2020; Zhao et al. 2016; Markides et al. 2007; Pantaleo
 153 et al. 2019): (a) The composition of particulate is pure carbon particles of the same size (b) The void
 154 space of the particulate deposition layer on the porous medium wall is randomly distributed, and its
 155 size is reasonably uniform; (c) In the same channel, the concentration of each exhaust component is
 156 distributed uniformly in the radial direction; (d) It is assumed that the exhaust is an incompressible
 157 ideal gas, which satisfies the ideal gas state equation; (e) Only the surface reactions of the
 158 components are considered during the regeneration process.

159 The mathematical regeneration models of the novel CGPFs are shown in the following
 160 equations.

161 (1) The mass conservation equation (E et al. 2020a):

$$162 \quad \frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho \cdot \vec{u}) = \sum_s w_s \quad (1)$$

163 (2) The momentum conservation equation (Zuo et al. 2021):

$$164 \quad \begin{cases} \frac{\partial(\rho u_x)}{\partial t} + \nabla \cdot (\rho \vec{u} u_x) = -\frac{\partial p}{\partial x} \nabla(\mu \cdot \text{gradu}_x) + F_x \\ \frac{\partial(\rho u_y)}{\partial t} + \nabla \cdot (\rho \vec{u} u_y) = -\frac{\partial p}{\partial y} \nabla(\mu \cdot \text{gradu}_y) + F_y \\ \frac{\partial(\rho u_z)}{\partial t} + \nabla \cdot (\rho \vec{u} u_z) = -\frac{\partial p}{\partial z} \nabla(\mu \cdot \text{gradu}_z) + F_z \end{cases} \quad (2)$$

165 (3) The component conservation equation (E et al. 2020b):

$$166 \quad \nabla \cdot (\rho \vec{u} Y_s) = - \left[\frac{\partial}{\partial x} \left(\rho D_s \frac{\partial Y_s}{\partial x} \right) + \frac{\partial}{\partial y} \left(\rho D_s \frac{\partial Y_s}{\partial y} \right) + \frac{\partial}{\partial z} \left(\rho D_s \frac{\partial Y_s}{\partial z} \right) \right] + W_s \quad (3)$$

167 (4) The electric heating catalytic reaction rate equation (Jiao et al. 2017):

$$168 \quad T_1 = \frac{P \cdot 3600}{E_1 \cdot C_e \cdot Q_e \cdot t} + T_0 \quad (4)$$

$$K_s = AT^B \exp(-E_a/R_0T) \quad (5)$$

2.3 Numerical model

The software Fluent is used to solve the above models. The component transport model and standard $k-\varepsilon$ model are applied to dispose of the chemical reaction model and flow model (White et al. 2018). The second-order upwind scheme is selected to discretize each governing equation (Zhao et al. 2020; Deng et al. 2017). The residual error of energy equation is 1×10^{-6} , while the residual error of continuity, momentum, and component equations is 1×10^{-3} . **Table 3** shows the initial boundary conditions.

Table 3. Initial boundary conditions

Parameters	Values
Flow rate	20 g/s
Heating power	0.5 kW
Exhaust oxygen concentration	1.6%
Exhaust NO concentration	800 ppm
Particulate mass concentration	$1 \text{ g} \cdot \text{L}^{-1}$
Inlet boundary	Mass flow inlet
Outlet boundary	Pressure outlet

The surface reaction mechanisms in CGPFs are shown in **Table 4**. Among them, in the inner and outer carriers, reaction 1 and reaction 2 are performed, and in the filter, all reactions are performed.

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Table 4 Main reaction mechanism (Jiao et al. 2017).

No.	Elementary reactions	Frequency factor (s^{-1})	Activation energy (kJ/mol)
R ₁	$NO + 1/2O_2 \rightarrow NO_2$	1.0E+13	600
R ₂	$NO_2 \rightarrow NO + 1/2O_2$	2.0E+12	26825
R ₃	$C(s) + NO_2 \rightarrow CO + NO$	3.9E+13	177
R ₄	$C(s) + 1/2O_2 \rightarrow CO$	2.0E+13	576
R ₅	$CO + 1/2O_2 \rightarrow CO_2$	2.5E+12	47800

183 **2.4 Grid independence research**

184 By using Fluent Meshing software, the grid independence of the novel CGPFs has been
185 explored, and three kinds of mesh models with different mesh number coupling polyhedron and
186 regular hexahedron are generated.

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Fig. 3. The medium mesh model.

189 The grid numbers of the three mesh models are 641,303 (fine mesh models), 238,105 (medium

190 mesh model), and 104,309 (coarse mesh model), respectively. In order to obtain the grid model in
 191 detail, **Fig 3** shows the medium grid mesh model of the novel CGPFs.

192 **Fig. 4** shows the distribution pattern of the mass concentration of particulate in different grid
 193 models. As we can see from the figure, when the dimensionless distances are identical, the
 194 difference of particulate mass concentration between the medium mesh model and the fine mesh
 195 model is basically the same. Therefore, considering the impact of the number of grids on the
 196 computational resources, the grid model with 238,105 grids can meet the requirements of the
 197 numerical simulation accuracy and shorten the calculation time.

198
 199 **Fig. 4.** Effects of the grid numbers on particulate mass concentration

200 2.5 experimental verification

201 In order to determine the accuracy of the simulation calculation results, the novel CGPFs
 202 models are validated according to experiment tests. **Fig. 5** shows the experimental equipment.

203 The experimental types of equipment are composed of the electric dynamometer, gasoline
 204 engine, flowmeter, differential pressure sensor, GPF, gas analyzer, computer, valve, power supply,

etc. The electric heating energy is provided by consuming a certain amount of fuel. Some key information about the GDI engine is listed in **Table 5**.

Fig. 5. Various experimental equipment used in the experiment test

Table 5 Technical parameters of the GDI engine

SN	Parameter	value
1	Engine displacement (L)	1.3
2	Cylinder number	4
3	Arrangement form	Transverse position
4	Bore diameter (mm)	71
5	stroke (mm)	82
6	Rated speed (rpm)	5400

The test dynamometer model is AC-110T electric dynamometer, which can be used to detect engine speed, torque, power and other operating parameters. Its rated power is 110 kW, rated torque is 175 N·m (error: $\leq \pm 0.28$ N·m), and rated speed is 6000 r/min (error: $\leq \pm 1$ r/min). The

213 DiCom-4000 gas analyzer produced by AVL is used to detect pollutants such as HC, CO, CO₂, NO_x
 214 and O₂ in the exhaust gas of gasoline engines. The basic technical parameters are shown in **Table 6**.

215 **Table 6** The DiCom-4000 gas analyzer related parameters

Pollutant compositions	Measuring ranges	errors
HC	0-2%	±0.0001%
CO	0-10%	±0.01%
CO ₂	0-20%	±0.1%
NO _x	0-5000ppm	±1ppm
O ₂	0-23%	±0.01%

216 As we can see from **Fig.6(a)**, it is clear that the relative error of the mass fraction of NO₂
 217 ranges from 2.8% to 3.9%, with a maximum relative error of less than 5%. As we can see from
 218 **Fig.6(b)**, it is clear that the relative error of the pressure drop ranges from 2.6% to 3.7%, with a
 219 maximum relative error of less than 5%. Thus, it shows good agreement between the experimental
 220 and simulation results. However, due to model simplification, experimental measurement error, and
 221 experimental instrument accuracy, there is still some discrepancy between the two results, but the
 222 difference is small (less than 5%).

223 The main reasons for the error of the numerical value are as follows (Zhang et al. 2017;
 224 Arunachalam et al. 2020): (1) In the simulation process, the flow of the exhaust gas in each channel
 225 is uniform in the radial direction, but in fact, the flow in each channel is not completely uniform. (2)
 226 There are unavoidable errors in the test process. (3) In the simulation process, the boundary
 227 conditions of the intake pipe and outlet pipe are adiabatic walls, but in fact, there is a heat transfer

phenomenon. Therefore, the mathematical models of the novel CGPFs meet the requirements of numerical simulation calculations and can be used to predict flow and reaction characteristics.

Fig. 6. Comparison of the experimental values and simulation values

2.6 Property comparison analysis

In this work, the NO_x conversion efficiency β can be defined as:

$$\beta = \frac{NO_{m,in} - NO_{m,out}}{NO_{m,in}} \times 100\% \quad (6)$$

The particulate combustion efficiency ε can be defined as:

$$\varepsilon = \frac{S_{m,in} - S_{m,out}}{S_{m,in}} \times 100\% \quad (7)$$

The regeneration property of conventional and novel CGPFs at different exhaust temperatures is compared and analyzed by changing only the exhaust temperature while the electric heating power is constant at 0.5kW and other operating conditions are the same. **Fig. 7(a)** and **Fig. 7(b)** show the variation patterns of catalytic efficiency of NO and combustion efficiency of particulate of the two CGPFs at various temperatures, respectively.

From **Fig. 7(a)**, we can see that the catalytic efficiency of NO of both CGPFs shows a tendency to increase and then decrease as the exhaust temperature increase. The novel CGPFs have a higher catalytic efficiency of NO at identical temperatures. The maximum values of NOx conversion efficiency for both conventional and novel CGPFs are obtained at 590 K, with values of 58.6% and 61.8%, respectively. Thus, the maximum NOx conversion efficiency of the novel CGPFs increases by 3.2%.

As we can see from **Fig. 7(b)**, the combustion efficiency of particulate in both CGPFs shows a tendency to increase rapidly and then stabilize with the increase of exhaust temperature. At identical exhaust temperatures, the novel CGPFs have higher particulate combustion efficiency. At an exhaust temperature of 590 K, the combustion efficiency of particulate is 74.1% and 76.8% for the conventional and novel CGPFs, respectively, and the novel CGPFs increase the particulate combustion efficiency by 2.7%. In summary, the novel CGPFs can improve the catalytic efficiency

257 of NO and combustion efficiency of particulate at identical working states.

(a) NOx conversion efficiency

(b) Particulate combustion efficiency

Fig. 7. Comparison results of the two CGPFs at various temperatures.

263 3. Results and discussions

264 In order to analyze the effect of different influencing parameters on the emission control of

gasoline vehicle exhaust pollutants, the effects of exhaust flow v_f , exhaust oxygen concentration C_o , exhaust NO concentration C_{NO} and electric heating power P_e on NOx conversion efficiency and particulate combustion efficiency are investigated in detail.

3.1 Influence analysis of NOx conversion efficiency

Fig. 8(a) shows the effect of v_f on the NOx conversion efficiency at various exhaust temperatures. From the figure, the NOx conversion efficiency at different v_f tends to increase and then decrease. At exhaust temperatures equal to 500 K, the NOx conversion efficiency at the v_f of 24 g/s, 20 g/s, and 16 g/s are 20%, 27%, and 38%, respectively. This is due to the low catalyst activity at low exhaust temperatures. With increasing exhaust temperature, CGPFs with low v_f reach their maximum NOx conversion efficiency at a lower temperature, and the maximum NOx conversion efficiency is higher. The maximum conversion efficiency of NOx is enhanced from 57% to 66% as the v_f decreases from 24 g/s to 16 g/s. This is because as the exhaust gas composition remains unchanged, the lower v_f results in slower exhaust flow velocity in the CGPFs, which increases the time for the catalyst coating in the carrier areas to come into contact with the exhaust gas. At the identical time, the exhaust gas heats up for a longer time in the heating area and the temperature of the exhaust gas rises higher, leading to a more complete reaction of NO with the oxidizer in the presence of the catalyst. At higher exhaust temperatures, the rate of NO₂ decomposition gradually exceeds the rate of NO catalytic reaction. Thus, the conversion efficiency of NOx starts to decrease with increasing temperature. Define the catalytic efficiency of NO above 50% as the reliable working temperature interval. Therefore, a proper reduction of the v_f is beneficial for increasing the NOx conversion efficiency and increasing the reliable working

286 temperature range.

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Fig.8. NOx conversion efficiency

Fig. 8(b) shows the effect of the C_o on the NOx conversion efficiency at various exhaust temperatures. From the figure, the conversion efficiency of NOx under various C_o conditions tends to increase and then decrease. At identical temperatures, the conversion efficiency of NOx is higher at higher C_o conditions. At the exhaust temperature of 500 K, the conversion efficiency of NOx is 18.3%, 25.5%, and 31.5% at an C_o of 1.2%, 1.6%, and 2.0%, respectively. The maximum conversion efficiency of NOx under different C_o conditions is reached at an exhaust temperature of

590K. The maximum conversion efficiency of NO_x is enhanced from 54% to 67% with the C_o increases from 1.2% to 2.0%. This is because that oxygen is the reactant in the catalytic reaction of NO_x, accelerates the rate of reaction in the presence of a catalyst when the C_o is increased. As a result, the NO_x conversion efficiency is higher at higher C_o at identical exhaust temperatures. At higher exhaust temperatures, the rate of NO₂ decomposition gradually exceeds the rate of NO catalytic reaction. Thus, the NO_x conversion efficiency gradually decreases with increasing temperature. Based on the determination of the reliable working temperature range, an appropriate increase in C_o is beneficial for increasing the NO_x conversion efficiency and increasing the reliable working temperature range.

Fig. 8(c) shows the influence of the C_{NO} on the NO_x conversion efficiency at various exhaust temperatures. From the figure, the NO_x conversion efficiency at different NO concentrations tends to increase and then decrease. The conversion efficiency of NO_x is higher at higher C_{NO} conditions at identical temperatures. The efficiency of NO_x is around 27% at 600 ppm, 800 ppm, and 1000 ppm of different C_{NO} conditions at 500 K. As the C_{NO} increases from 600 ppm to 1000 ppm, the maximum NO_x conversion efficiency is increased from 60.7% to 62.2%. This is because although NO is used as a reactant in the catalytic reaction, in exhaust gas, the oxygen concentration is much higher than the C_{NO} , and increasing the NO concentration has less effect on the catalytic reaction. As the NO concentration in the exhaust gas increases, the catalytic reaction under different C_{NO} conditions can reach a complete reaction state. Therefore, at identical exhaust temperatures, the C_{NO} has less influence on the NO_x conversion efficiency. At higher exhaust temperatures, the rate of NO₂ decomposition gradually exceeds the rate of NO_x catalytic reaction. Thus, the NO_x conversion

317 efficiency gradually decreases with increasing temperature. Based on the determination of the
318 reliable working temperature range, an appropriate increase in C_{NO} is beneficial for increasing the
319 NOx conversion efficiency and increasing the reliable working temperature range.

320 **Fig. 8(d)** shows the influence of P_e on the NOx conversion efficiency at various exhaust
321 temperatures. From the figure, the conversion efficiency of NOx at different P_e conditions tends to
322 increase and then decrease with the increases of exhaust temperature. The conversion efficiency of
323 NOx is 20%, 27%, and 35% at 0.3 kW, 0.5 kW, and 0.7 kW of P_e conditions at an exhaust
324 temperature of 500 K. This is due to the low catalyst activity at low exhaust temperatures. The
325 CGPFs with higher P_e condition reaches the maximum NOx conversion efficiency at lower exhaust
326 temperature with increasing exhaust temperature, and the maximum conversion efficiencies of NOx
327 at various P_e conditions are the same. The maximum conversion efficiency of NOx is maintained at
328 62% when the P_e enhances from 0.3 kW to 0.7 kW. This is mainly because the composition and
329 flow characteristics of the exhaust gas remain unchanged, and the exhaust gas under different P_e
330 conditions can reach the same degree of reaction state. In the case of high P_e , the exhaust gas raises
331 the temperature in the heated area faster. Therefore, when the P_e is high, the NO catalytic reaction
332 and the NO₂ decomposition reaction reach equilibrium more quickly. At higher exhaust
333 temperatures, the rate of NO₂ decomposition gradually exceeds the rate of NO catalytic reaction.
334 Thus, the NOx conversion efficiency gradually decreases with increasing temperature. Thus, an
335 appropriate increase in P_e is beneficial for increasing the NOx conversion efficiency and increasing
336 the reliable working temperature range.

337 *3.2 Influence analysis of particulate combustion efficiency*

338 **Fig. 9(a)** shows the pattern of the effect of v_f on the combustion efficiency of particulate at
339 various exhaust temperatures. From the figure, the particulate combustion efficiency at different v_f
340 conditions shows a tendency to increase rapidly and then stabilize with increasing temperature.
341 When the v_f is lower, the combustion efficiency of particulate is greater at identical exhaust
342 temperatures. The combustion efficiency of particulate is less than 25% at exhaust temperatures
343 equal to 500 K, and the combustion efficiency of particulate is greater than 90% at exhaust
344 temperatures greater than 650 K. This is because that the catalyst activity gradually increases and
345 the rate of particulate oxidation accelerates, which causes the particulate combustion efficiency to
346 increase rapidly while the exhaust temperature enhances. When the v_f is low, the convective heat
347 exchange of the exhaust gas in the heated area is enhanced and the exhaust gas temperature rises
348 higher. As a result, at identical exhaust temperatures, the combustion efficiency of particulate is
349 higher at lower v_f .

350 **Fig. 9(b)** shows the pattern of the effect of C_o on the particulate combustion efficiency at
351 various exhaust temperatures. From the figure, the particulate combustion efficiency at different C_o
352 conditions shows a tendency to increase rapidly and then stabilize with increasing temperature. At
353 identical exhaust temperatures, the combustion efficiency of particulate is higher while the C_o
354 condition is greater. At exhaust temperatures equal to 500 K, the oxidation efficiencies of particulate
355 are less than 20% at different C_o conditions, and the oxidation efficiencies of particulate are greater
356 than 90% at exhaust temperatures greater than 635 K. This is because that the catalyst activity
357 gradually increases and the rate of particulate oxidation accelerates with the exhaust temperature
358 increases, resulting in a rapid increase in the rate of particulate oxidation. As the C_o increases, the

359 rate and amount of NO_2 generation in the carrier areas increases, resulting in a larger NO_2
 360 concentration in the exhaust gas, which contributes to an enhance in the particulate combustion
 361 efficiency. As a result, at identical exhaust temperatures, the combustion efficiency of particulate is
 362 higher at greater C_o conditions. Thus, an appropriate increase in C_o will help to reach a more
 363 effective particulate cleaning effect.

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Fig. 9. Particulate combustion efficiency.

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Fig. 9(c) shows the pattern of the influence of C_{NO} on the particulate combustion efficiency at
 various exhaust temperatures. From the figure, the particulate combustion efficiency at different

369 C_{NO} conditions shows a tendency to increase rapidly and then stabilize with increasing temperature.
370 The combustion efficiency of particulate is higher when the C_{NO} condition is greater at identical
371 exhaust temperatures. The oxidation efficiencies of particulate are less than 20% at different C_{NO}
372 conditions at 500 K, and the oxidation efficiencies of particulate are greater than 90% at exhaust
373 temperatures greater than 635 K. This is because that the temperature is low, resulting in a lower
374 rate of oxidation. The catalyst activity gradually increases and the rate of particulate oxidation
375 accelerates as the exhaust temperature increases, resulting in a rapid increase in the rate of
376 particulate oxidation. As the C_{NO} increases, the NO_2 concentration at the carrier outlet also increases,
377 resulting in a faster combustion efficiency of particulate in the filter area. As a result, at identical
378 exhaust temperatures, the combustion efficiency of particulate is higher at greater C_{NO} . Thus, an
379 appropriate increase in C_{NO} will help to reach a more effective particulate cleaning effect.

380 **Fig. 9(d)** shows the pattern of the influence of P_e on the particulate combustion efficiency at
381 various exhaust temperatures. From the figure, the particulate combustion efficiency at different P_e
382 conditions shows a tendency to increase rapidly and then stabilize with increasing temperature. At
383 identical exhaust temperatures, the combustion efficiency of particulate is higher while the P_e is
384 larger. At exhaust temperatures equal to 500 K, the oxidation efficiencies of particulate are less than
385 25% at various P_e conditions. This is because that the temperature is low, resulting in a lower rate of
386 oxidation. The catalyst activity gradually increases and the rate of particulate oxidation accelerates
387 as the exhaust temperature increases, resulting in a rapid increase in the rate of particulate oxidation.
388 When the P_e is higher, the exhaust gas temperature increases even more. The oxidation efficiencies
389 of particulate are greater than 90% at exhaust temperatures greater than 635 K. Therefore, at

390 identical exhaust temperatures, the combustion efficiency of particulate is higher with larger P_e .
391 Thus, an appropriate increase in P_e will help to reach a more effective particulate cleaning effect.

392 **3.3 The distribution pattern of NO mass fraction**

393 From **Fig. 10(a)**, the mass fraction of NO decreases gradually with increasing dimensionless
394 distance x/L_1 at different v_f . The mass fraction of NO decreases faster at lower v_f , and the mass
395 fractions of NO are minimized at the carrier outlet at different v_f . As the v_f reduces from 24 g/s to 16
396 g/s, the minimum NO mass fraction value is reduced from 342 ppm to 285 ppm. The result is
397 mainly due to the longer contact time between the exhaust gas and the catalyst coating in the carrier
398 areas as the v_f decreases, while convective heat transfer is enhanced and the exhaust gas temperature
399 increases, which results in a faster decrease in NO mass fraction. Thus, a proper reduction of the v_f
400 is beneficial to the NOx conversion efficiency.

401 As we can see from **Fig. 10(b)**, the mass fraction of NO decreases gradually with increasing
402 dimensionless distance x/L_1 at different C_o conditions. The mass fraction of NO decreases faster at
403 greater C_o conditions, and the mass fraction of NO is minimized at the carrier outlet at different C_o
404 conditions. With the C_o increases from 1.2% to 2.0%, the minimum NO mass fraction value is
405 reduced from 368 ppm to 264 ppm. This is mainly because when the C_o increases, the catalytic
406 reaction rate of the exhaust gas is accelerated by the catalyst, resulting in a quicker catalytic
407 reaction efficiency and a rapid decrease in the NO mass fraction. Thus, an appropriate increase in
408 C_o is beneficial for increasing the NOx conversion efficiency.

Fig. 10. The distribution pattern of NO mass fraction

As we can see from **Fig. 10(c)**, the mass fraction of NO decreases gradually with increasing dimensionless distance x/L_1 at different C_{NO} conditions. The mass fraction of NO decreases faster at greater oxygen concentrations, and the mass fraction of NO is minimized at the carrier outlet at different C_{NO} conditions. As the C_{NO} increases from 600 ppm to 1000 ppm, the minimum mass fraction value of NO is increased from 236 ppm to 378 ppm. This is mainly because as the C_{NO} increases, the NO concentration increases correspondingly at the inlet of the carrier areas. Among the gasoline exhaust gases, since the catalytic efficiency of NO is almost the same for different C_{NO}

419 conditions, the exhaust gas with higher NO concentration has a higher NO mass fraction at the same
420 dimensionless distance. Thus, an appropriate increase in C_{NO} is beneficial for increasing the NO_x
421 conversion efficiency.

422 As we can see from **Fig. 10(d)**, the mass fractions of NO decreases gradually with increasing
423 dimensionless distance x/L_1 at various P_e conditions. The mass fraction of NO decreases faster at
424 larger P_e conditions, and the mass fraction of NO is minimized at the carrier outlet under various P_e
425 conditions. The minimum mass fraction values of NO are 310 ppm, 307 ppm, and 317 ppm at
426 0.3kW, 0.5kW, and 0.7kW of heating power, respectively. This is mainly because the NO catalytic
427 reaction is almost complete at 0.3 kW of P_e , and a further increase in heating power does not
428 increase the catalytic efficiency of NO significantly. Therefore, the minimal mass fraction of NO
429 varies less for different P_e conditions.

430 **4. Orthogonal experiment design and analysis**

431 **4.1 Experimental scheme design**

432 To use partial experiments instead of comprehensive experiments, the range analysis method
433 of orthogonal experiment is used to analyze the primary and secondary effects of different factors
434 on the integrated t regeneration property of the novel CGPFs (Zuo et al. 2018; Zuo et al. 2019). The
435 influencing factors include the flow rate v_F , oxygen concentration C_o , NO concentration C_{NO} and
436 heating power P_e . **Table 7** shows the designed schemes of orthogonal experiment, which include 9
437 examples.

438

439

440

Table 7 Orthogonal table

Examples	v_f	C_o	C_{NO}	P_e
1	16 g/s	1.2%	1000 ppm	0.3 kW
2	16 g/s	1.6%	800 ppm	0.5 kW
3	16 g/s	2.0%	600 ppm	0.7 kW
4	20 g/s	1.2%	800 ppm	0.7 kW
5	20 g/s	1.6%	600 ppm	0.3 kW
6	20 g/s	2.0%	1000 ppm	0.5 kW
7	24 g/s	1.2%	600 ppm	0.5 kW
8	24 g/s	1.6%	1000 ppm	0.7 kW
9	24 g/s	2.0%	800 ppm	0.3 kW

441 **4.2 The results of orthogonal experiment**

442 The simulation is completed by using the orthogonal experiment schemes in **Table 7**, and the
443 NOx conversion efficiency and particulate combustion efficiency of the 9 examples are obtained.
444 **Fig. 11** shows the simulation results of the 9 examples.

445 In **Fig. 11(a)**, it is clearly seen that the average NOx conversion efficiency of the 9 examples is
446 59.7%. Compared with other examples, the NO catalytic efficiencies of examples 1, 4 and 7 are far
447 less than the average value, while those of examples 3, 6 and 9 are far greater than the average
448 value. Combined with **Table 7**, it is found that the flow rate v_f is the key factor affecting the NOx
449 conversion efficiency.

(a) NOx conversion efficiency

(b) Particulate combustion efficiency

Fig. 11. Orthogonal experiment results of NOx conversion efficiency and particulate combustion efficiency

In **Fig. 11(b)**, it is clearly seen that the average particulate combustion efficiency of the 9 examples is 74.8%. Compared with other examples, the particulate oxidation efficiencies of examples 7, 8 and 9 are far less than the average value, while those of examples 1, 2 and 3 are far

458 greater than the average value. Combined with **Table 7**, it is found that the oxygen concentration C_o
 459 is the key factor affecting the particulate combustion efficiency.

460 Based on the results of the orthogonal experiment, the range percentage of different factors
 461 affecting the NOx conversion efficiency and particulate combustion efficiency is calculated through
 462 the range analysis method (Lin et al. 2019), as shown in **Fig. 12**. As we can see from the figure, the
 463 range percentages of v_f , C_o , C_{NO} , and P_e on NOx conversion efficiency are 29.9%、48%、14.8%、and
 464 7.3%, respectively. The range percentages of particulate combustion efficiency are 35.9%、15%、
 465 23.6%, and 25.5%, respectively. Therefore, the primary and secondary effect of each factor on the
 466 catalytic efficiency of NO is $C_o > v_f > C_{NO} > P_e$. The primary and secondary effect of each factor on
 467 the particulate combustion efficiency is $v_f > C_o > C_{NO} > P_e$.

468
 469 **Fig.12.** Range percentage of each influencing factor

470 4.3 Optimal results

471 As we can see from **Fig. 13**, the novel CGPFs can reach a high catalytic efficiency of NO and
 472 combustion efficiency of particulate when the v_f is 16 g/s, the C_o is 2.0%, the C_{NO} is 600 ppm, and

473 the P_e is 0.7 kW. The catalytic efficiency of NO is increased by 3.6% and the combustion efficiency
474 of particulate is increased by 16.7% with a 0.2 kW increase in electric heating power compared to
475 the initial condition.

476
477 **Fig. 13.** Comparison of optimal results.

478 **5. Conclusions**

479 Current researches on CGPFs focused primarily on various influence factors such as structural
480 parameters, intake parameters, and different regeneration technologies on the individual catalytic
481 converter and particulate filter interior flow field, pressure drop and regeneration rate. A
482 comprehensive in-depth investigation of the NO_x conversion efficiency and particulate combustion
483 efficiency of CGPFs is relatively lacking. Therefore, to enhance the flow uniformity and the NO_x

484 conversion efficiency and particulate combustion efficiency at low exhaust temperature conditions,
485 the physical and mathematical models of a novel CGPFs are proposed based on the computational
486 fluid dynamics software. The influence patterns of different influencing factors on the NO_x
487 conversion efficiency and particulate combustion efficiency of CGPFs are investigated. The main
488 findings are as follows:

489 (1) Properly reducing the flow rate v_f is conducive to improving the NO_x conversion efficiency and
490 particulate combustion efficiency. The maximal catalytic efficiency of NO is enhanced from 57% to
491 66% as the v_f decreases from 24 g/s to 16 g/s. The NO mass fraction at the carrier outlet is reduced
492 from 342 ppm to 285 ppm when the v_f reduces from 24 g/s to 16 g/s.

493 (2) Properly increasing the oxygen concentration C_o is conducive to improving the NO_x conversion
494 efficiency and particulate combustion efficiency. The maximal catalytic efficiency of NO is
495 enhanced from 54% to 67% with the C_o increases from 1.2% to 2.0%. The NO mass fraction at the
496 carrier outlet decreases from 368 ppm to 264 ppm when the C_o increases from 1.2% to 2.0%.

497 (3) Properly increasing the NO concentration C_{NO} is conducive to improving the NO_x conversion
498 efficiency and particulate combustion efficiency. The maximal catalytic efficiency of NO is
499 enhanced from 60.7% to 62.2% with the C_{NO} increases from 600 ppm to 1000 ppm. The minimal
500 mass fraction value of NO is increased from 236 ppm to 378 ppm while the C_{NO} increases from 600
501 ppm to 1000 ppm.

502 (4) Properly increasing the heating power P_e is conducive to improving the NO_x conversion
503 efficiency and particulate combustion efficiency. The maximal catalytic efficiency of NO is
504 maintained at 62% as the P_e increases from 0.3 kW to 0.7 kW. The combustion efficiency of

505 particulate is higher while the P_e is greater at identical exhaust temperatures.

506 (5) The novel CGPFs can reach a high catalytic efficiency of NO and combustion efficiency of
507 particulate when the v_f is 16 g/s, the C_o is 2.0%, the C_{NO} is 600 ppm, and the P_e is 0.7 kW. The
508 catalytic efficiency of NO is increased by 3.6% and the combustion efficiency of particulate is
509 increased by 16.7% with a 0.2 kW increase in electric heating power compared to the initial
510 condition.

511 **Authors' contributions**

512 **Yong Xie:** Software, Data curation, Writing-Original Draft, Formal analysis. **Qingsong Zuo:**
513 Resources, Funding acquisition, Project administration, Data curation, Writing-Original Draft.
514 **Qingwu Guan:** Data curation. **Kexiang Wei:** Conceptualization, Methodology. **Bin Zhang:** Formal
515 analysis.

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520 **Data availability**

521 The present study data are available from the corresponding author on reasonable request.

522 **Competing interests**

523 The authors declare that they have no competing interests.

524 **Availability of data and materials**

525 All data generated or analyzed during this study are included in this published article.

526 **Ethical approval and consent to participate**

527 This article does not contain any studies with human participants or animals.

528 **Consent for publication**

529 Not applicable.

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