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

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

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Abstract: Improving the NOx 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 NOx 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 $v_i$, exhaust oxygen concentration $C_o$, exhaust NO concentration $C_{NO}$ and electric heating power $P_e$ on the NOx conversion efficiency and particulate combustion efficiency are investigated. The weights of each influencing parameter on the NOx conversion efficiency and particulate combustion efficiency are explored by orthogonal tests. The conclusions show that the NOx conversion efficiency is increased
by 3.6% and the particulate combustion efficiency is increased by 16.7% compared to the initial condition. This study has an important reference value for improving the purification efficiency of vehicle emission under cold start conditions.

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

- $T_i$: the target exhaust gas temperature, K;
- $P$: the heating power, kW;
- $\rho$: the density of exhaust gas, kg/m$^3$;
- $E_1$: heat transfer coefficient, 1.2~1.3;
- $\bar{u}$: 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;
- $K_i$: the component $s$ reaction rate, mol/(L·s);
- $p$: pressure, Pa;
- $A$: apparent activation energy, J/mol;
- $\mu$: 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;
- $NO_{m,out}$: mass fraction of NO in outlet, ppm;
- $Y_s$: the exhaust component $s$ mass percentage, %;
- $S_{m,in}$: mass concentration of particulate in inlet, %;
- $S_{m,out}$: mass concentration of particulate in outlet, %;
1. Introduction

The amount of particulate emissions from gasoline vehicles has already attracted worldwide attention as the number of gasoline vehicles increases rapidly (Wang et al. 2018; Sthel et al. 2019). Increasing the number of particulate emissions will not only seriously endanger human health, but also lead to the formation of disastrous weather (Qian et al. 2019; Dai et al. 2019). Nowadays, although homogeneous mixing technology (Xu et al. 2020) and laminar oxidation technology (Zhong et al. 2016; Distaso et al. 2019) have been successfully applied to gasoline vehicles, the particulate emission of the gasoline vehicles still cannot meet the increasingly stringent emission standards (Jain et al. 2017; Chen et al. 2017). Therefore, reducing the particulate emission of gasoline vehicles has become an urgent problem to be solved (Wang et al. 2020). Catalytic gasoline particulate filter system (CGPFs) is currently regarded as one of the most useful automotive exhaust post-treatment technologies (Zuo et al. 2021; Du et al. 2015). As shown in Fig. 1, the post-treatment system of the gasoline engine comprises a catalytic converter and a particulate filter (Zhong et al. 2021; Jiang et al. 2017). First, the exhaust gas generated during the vehicle load process enters the catalytic converter (Zhang et al. 2016). When the catalytic converter is working, the HC and CO of the exhaust gas are purified, and NO is converted into NO₂ (Bermudez et al. 2015; E et al. 2020). Then, the exhaust gas with sufficient NO₂ concentration flows into the particulate filter (Chen et al. 2014). In the particulate filter, the particles react with NO₂ to generate clean exhaust gas (Caliskan et al. 2017; E et al. 2016). Finally, the clean exhaust gas flows into the atmosphere from the outlet of the CGPFs.
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 NOx and PM in DPF, and explored the reaction process of NOx and PM under different inlet conditions. The results showed that when the NO$_2$ in the inlet exhaust accounted for 0.7~0.8 of the total NOx content, particulate had a good regeneration effect; when the molar ratio of NOx 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.
Ko et al. (2019) analyzed the particle number (PN) emission characteristics of GDI vehicles with and without gasoline particulate filter (GPF) under cold-start conditions. The results showed that the PN emissions of GDI vehicles with GPF were significantly reduced at higher engine speed conditions. Bock et al. (2020) investigated the ability of catalytic GPF to treat dicarboxylic acids in ethanol-blended gasoline emissions according to an experimental method. It was found that the catalytic GPF was able to remove 80% to 92% of the dicarboxylic acids from the engine exhaust. E et al. (2020) made a discussion on the effects of various factors on the particulate oxidation property of DPF. They concluded that the particulate oxidation property could be enhanced as the exhaust temperature was 600-750 K, the particulate concentration was 0.06-0.08, and the microwave heating power was 800-1200 W.

In the study of catalytic converters, Mianzarasvand et al. (2017) researched the effects of electric heating temperatures and heating times on catalytic converters. They found that the heating temperature was at least 450°C, and the heater was required to start 35 s in advance. Broatch et al. (2008) made an in-depth analysis of the intake air heating technology of catalytic converters. They claimed that compared with the electric plug, the intake heating technology can reduce HC emissions by 13%, CO emissions by 5%, and NO emissions by 3%. Horng et al. (2004) investigated the effects of heating energy and CO content of catalytic converter on CO conversion rate. The results revealed that the CO conversion efficiency was improved when the heater was located at the inlet. Vaishnav et al. (2014) explored catalytic converters with diffuser devices at the inlet and demonstrated that the structure optimized the exhaust flow route and improved the purification effect. Day et al. (2020) surveyed various catalysts in catalytic converters, revealed that compared
with noble metal catalysts, Cu was the most powerful and active catalyst for CO. Ibrahim et al. (2018) proposed that insulating material was placed in the carrier channel to investigated the distribution of the internal flow field and the change of heat diffusion. They found that the gas uniformity and thermal properties were improved by 5% and 18%, respectively.

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

Therefore, to enhance the NOx conversion efficiency and particulate combustion efficiency at low exhaust temperature conditions, the physical and mathematical models of a novel CGPFs are proposed based on the computational fluid dynamics software. The properties of conventional and novel CGPFs are analyzed comparatively, and the computational models are validated according to
experiments. Finally, the influences of flow rate, NO concentration, oxygen concentration, and heating power on the regeneration property of the novel CGPFs are investigated. The weights of each influencing parameter on the NOx conversion efficiency and particulate combustion efficiency are explored by orthogonal tests, and the novel CGPFs is also preferentially selected under simulated working conditions. This work will provide a theoretical basis for further enhancing the purification efficiency of vehicle emission under cold start conditions.

2. The novel CGPFs model construction

2.1 Physical model

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

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

(a) The gasoline engine exhaust gas in low temperature operation flows from the inlet tube into the expansion tube region and is heated by the electric heating equipment in the expansion tube region.

(b) The heated exhaust gas undergoes a catalytic reaction in both carrier regions, where the main pollutants of the exhaust gas are purified and NOx is converted to NO2.

(c) The particulate in the exhaust is trapped by the filter and oxidized by NO2 in the filter region, so as to remove the particulate and achieving the objective of purifying the exhaust gas.

(d) The purified gasoline engine exhaust gases are discharged from the shrink tube region and outlet tube region.
Fig. 2. The geometry of the novel CGPFs.

Table 1 The structural parameters.

<table>
<thead>
<tr>
<th>Structures</th>
<th>Inlet pipe</th>
<th>Expansion pipe</th>
<th>Outer carrier</th>
<th>Inner carrier</th>
<th>Air gap</th>
<th>Filter pipe</th>
<th>Shrink pipe</th>
<th>Outlet pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length(mm)</td>
<td>25</td>
<td>25</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Diameter(mm)</td>
<td>47</td>
<td>/</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>/</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 2 shows the carriers and filter related structural parameters.

Table 2 The carrier and filter related structural parameters.

<table>
<thead>
<tr>
<th>Structures</th>
<th>Material</th>
<th>Pore density (cpsi)</th>
<th>Wall thickness (mm)</th>
<th>Channel diameter (mm)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer carrier</td>
<td>Cordierite</td>
<td>400</td>
<td>1.10</td>
<td>0.17</td>
<td>75</td>
</tr>
<tr>
<td>Inner carrier</td>
<td>Cordierite</td>
<td>500</td>
<td>0.97</td>
<td>0.17</td>
<td>72</td>
</tr>
<tr>
<td>Filter</td>
<td>SiC</td>
<td>325</td>
<td>1.01</td>
<td>0.40</td>
<td>51</td>
</tr>
</tbody>
</table>

2.2 Mathematical model of the CGPFs

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

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

(1) The mass conservation equation (E et al. 2020a):
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \mathbf{u}) = \sum w_i
\]  
(1)

(2) The momentum conservation equation (Zuo et al. 2021):
\[
\begin{align*}
\frac{\partial (\rho u_x)}{\partial t} + \nabla \cdot (\rho \mathbf{u} \cdot \mathbf{u}_x) &= - \frac{\partial p}{\partial x} + \mu \nabla^2 u_x + F_x \\
\frac{\partial (\rho u_y)}{\partial t} + \nabla \cdot (\rho \mathbf{u} \cdot \mathbf{u}_y) &= - \frac{\partial p}{\partial y} + \mu \nabla^2 u_y + F_y \\
\frac{\partial (\rho u_z)}{\partial t} + \nabla \cdot (\rho \mathbf{u} \cdot \mathbf{u}_z) &= - \frac{\partial p}{\partial z} + \mu \nabla^2 u_z + F_z
\end{align*}
\]  
(2)

(3) The component conservation equation (E et al. 2020b):
\[
\nabla \cdot (\rho \mathbf{u} Y_x) = \left[ \frac{\partial}{\partial x} \left( \rho D_z \frac{\partial Y_x}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho D_z \frac{\partial Y_x}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho D_z \frac{\partial Y_x}{\partial z} \right) \right] + W_x
\]  
(3)

(4) The electric heating catalytic reaction rate equation (Jiao et al. 2017):
\[
T_i = \frac{P \cdot 3600}{E_i \cdot C_e \cdot Q_e \cdot t} + T_0
\]  
(4)
\[ K_s = AT^B \exp(-E_a/R_sT) \]  \hspace{1cm} (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 \( 1 \times 10^{-6} \), while the residual error of continuity, momentum, and component equations is \( 1 \times 10^{-3} \). Table 3 shows the initial boundary conditions.

**Table 3. Initial boundary conditions**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>20 g/s</td>
</tr>
<tr>
<td>Heating power</td>
<td>0.5 kW</td>
</tr>
<tr>
<td>Exhaust oxygen concentration</td>
<td>1.6%</td>
</tr>
<tr>
<td>Exhaust NO concentration</td>
<td>800 ppm</td>
</tr>
<tr>
<td>Particulate mass concentration</td>
<td>1 g·L(^{-1})</td>
</tr>
<tr>
<td>Inlet boundary</td>
<td>Mass flow inlet</td>
</tr>
<tr>
<td>Outlet boundary</td>
<td>Pressure outlet</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Elementary reactions</th>
<th>Frequency factor (s(^{-1}))</th>
<th>Activation energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(_1)</td>
<td>NO+1/2O(_2)→NO(_2)</td>
<td>1.0E+13</td>
<td>600</td>
</tr>
<tr>
<td>R(_2)</td>
<td>NO(_2)→NO+1/2O(_2)</td>
<td>2.0E+12</td>
<td>26825</td>
</tr>
<tr>
<td>R(_3)</td>
<td>C(s)+NO(_2)→CO+NO</td>
<td>3.9E+13</td>
<td>177</td>
</tr>
<tr>
<td>R(_4)</td>
<td>C(s)+1/2O(_2)→CO</td>
<td>2.0E+13</td>
<td>576</td>
</tr>
<tr>
<td>R(_5)</td>
<td>CO+1/2O(_2)→CO(_2)</td>
<td>2.5E+12</td>
<td>47800</td>
</tr>
</tbody>
</table>

#### 2.4 Grid independence research

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

![Fig. 3. The medium mesh model.](image)

The grid numbers of the three mesh models are 641,303 (fine mesh models), 238,105 (medium
mesh model), and 104,309 (coarse mesh model), respectively. In order to obtain the grid model in detail, Fig 3 shows the medium grid mesh model of the novel CGPFs.

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

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

2.5 experimental verification

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

The experimental types of equipment are composed of the electric dynamometer, gasoline 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**.

![Experimental equipment diagram](image)

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

**Table 5** Technical parameters of the GDI engine

<table>
<thead>
<tr>
<th>SN</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engine displacement (L)</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder number</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Arrangement form</td>
<td>Transverse position</td>
</tr>
<tr>
<td>4</td>
<td>Bore diameter (mm)</td>
<td>71</td>
</tr>
<tr>
<td>5</td>
<td>stroke (mm)</td>
<td>82</td>
</tr>
<tr>
<td>6</td>
<td>Rated speed (rpm)</td>
<td>5400</td>
</tr>
</tbody>
</table>

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: ± 0.28 N·m), and rated speed is 6000 r/min (error: ± 1 r/min). The
DiCom-4000 gas analyzer produced by AVL is used to detect pollutants such as HC, CO, CO\(_2\), NO\(_x\) and O\(_2\) in the exhaust gas of gasoline engines. The basic technical parameters are shown in Table 6.

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

<table>
<thead>
<tr>
<th>Pollutant compositions</th>
<th>Measuring ranges</th>
<th>errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>0-2%</td>
<td>±0.0001%</td>
</tr>
<tr>
<td>CO</td>
<td>0-10%</td>
<td>±0.01%</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0-20%</td>
<td>±0.1%</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>0-5000ppm</td>
<td>±1ppm</td>
</tr>
<tr>
<td>O(_2)</td>
<td>0-23%</td>
<td>±0.01%</td>
</tr>
</tbody>
</table>

As we can see from Fig.6(a), it is clear that the relative error of the mass fraction of NO\(_2\) ranges from 2.8% to 3.9%, with a maximum relative error of less than 5%. As we can see from Fig.6(b), it is clear that the relative error of the pressure drop ranges from 2.6% to 3.7%, with a maximum relative error of less than 5%. Thus, it shows good agreement between the experimental and simulation results. However, due to model simplification, experimental measurement error, and experimental instrument accuracy, there is still some discrepancy between the two results, but the difference is small (less than 5%).

The main reasons for the error of the numerical value are as follows (Zhang et al. 2017; Arunachalam et al. 2020): (1) In the simulation process, the flow of the exhaust gas in each channel is uniform in the radial direction, but in fact, the flow in each channel is not completely uniform. (2) There are unavoidable errors in the test process. (3) In the simulation process, the boundary 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.

![Graph showing NO\textsubscript{2} mass fraction and pressure drop](image_url)

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

### 2.6 Property comparison analysis

In this work, the NOx conversion efficiency $\beta$ can be defined as:
\[ \beta = \frac{\text{NO}_{\text{m, in}} - \text{NO}_{\text{m, out}}}{\text{NO}_{\text{m, in}}} \times 100\% \]  

(6)

The particulate combustion efficiency \( \varepsilon \) can be defined as:

\[ \varepsilon = \frac{S_{\text{m, in}} - S_{\text{m, out}}}{S_{\text{m, in}}} \times 100\% \]  

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

![Graph showing NO conversion efficiency and particulate combustion efficiency at various temperatures.](image)

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

### 3. Results and discussions

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 NO$_2$ 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
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
The maximum conversion efficiency of NOx is enhanced from 54% to 67% with the \( C_0 \)
increases from 1.2% to 2.0%. This is because that oxygen is the reactant in the catalytic reaction of
NOx, accelerates the rate of reaction in the presence of a catalyst when the \( C_0 \) is increased. As a
result, the NOx conversion efficiency is higher at higher \( C_0 \) at identical exhaust temperatures. At
higher exhaust temperatures, the rate of NO\(_2\) decomposition gradually exceeds the rate of NO
catalytic reaction. Thus, the NOx conversion efficiency gradually decreases with increasing
temperature. Based on the determination of the reliable working temperature range, an appropriate
increase in \( C_0 \) is beneficial for increasing the NOx conversion efficiency and increasing the reliable
working temperature range.

**Fig. 8(c)** shows the influence of the \( C_{NO} \) on the NOx conversion efficiency at various exhaust
temperatures. From the figure, the NOx conversion efficiency at different NO concentrations tends
to increase and then decrease. The conversion efficiency of NOx is higher at higher \( C_{NO} \) conditions
at identical temperatures. The efficiency of NOx 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 NOx 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 NOx conversion efficiency. At higher exhaust temperatures, the rate of
NO\(_2\) decomposition gradually exceeds the rate of NOx catalytic reaction. Thus, the NOx conversion
efficiency gradually decreases with increasing temperature. Based on the determination of the reliable working temperature range, an appropriate increase in $C_{NO}$ is beneficial for increasing the NOx conversion efficiency and increasing the reliable working temperature range.

**Fig. 8(d)** shows the influence of $P_e$ on the NOx conversion efficiency at various exhaust temperatures. From the figure, the conversion efficiency of NOx at different $P_e$ conditions tends to increase and then decrease with the increases of exhaust temperature. The conversion efficiency of NOx is 20%, 27%, and 35% at 0.3 kW, 0.5 kW, and 0.7 kW of $P_e$ conditions at an exhaust temperature of 500 K. This is due to the low catalyst activity at low exhaust temperatures. The CGPFs with higher $P_e$ condition reaches the maximum NOx conversion efficiency at lower exhaust temperature with increasing exhaust temperature, and the maximum conversion efficiencies of NOx at various $P_e$ conditions are the same. The maximum conversion efficiency of NOx is maintained at 62% when the $P_e$ enhances from 0.3 kW to 0.7 kW. This is mainly because the composition and flow characteristics of the exhaust gas remain unchanged, and the exhaust gas under different $P_e$ conditions can reach the same degree of reaction state. In the case of high $P_e$, the exhaust gas raises the temperature in the heated area faster. Therefore, when the $P_e$ is high, the NO catalytic reaction and the NO$_2$ decomposition reaction reach equilibrium more quickly. At higher exhaust temperatures, the rate of NO$_2$ decomposition gradually exceeds the rate of NO catalytic reaction. Thus, the NOx conversion efficiency gradually decreases with increasing temperature. Thus, an appropriate increase in $P_e$ is beneficial for increasing the NOx conversion efficiency and increasing the reliable working temperature range.

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

Fig. 9(b) shows the pattern of the effect of $C_0$ on the particulate combustion efficiency at various exhaust temperatures. From the figure, the particulate combustion efficiency at different $C_0$ conditions shows a tendency to increase rapidly and then stabilize with increasing temperature. At identical exhaust temperatures, the combustion efficiency of particulate is higher while the $C_0$ condition is greater. At exhaust temperatures equal to 500 K, the oxidation efficiencies of particulate are less than 20% at different $C_0$ conditions, and the oxidation efficiencies of particulate are greater than 90% at exhaust temperatures greater than 635 K. This is because that the catalyst activity gradually increases and the rate of particulate oxidation accelerates with the exhaust temperature increases, resulting in a rapid increase in the rate of particulate oxidation. As the $C_0$ increases, the
rate and amount of NO₂ generation in the carrier areas increases, resulting in a larger NO₂ concentration in the exhaust gas, which contributes to an enhance in the particulate combustion efficiency. As a result, at identical exhaust temperatures, the combustion efficiency of particulate is higher at greater $C_0$ conditions. Thus, an appropriate increase in $C_0$ will help to reach a more effective particulate cleaning effect.

Fig. 9. Particulate combustion efficiency.

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
$C_{NO}$ conditions shows a tendency to increase rapidly and then stabilize with increasing temperature. The combustion efficiency of particulate is higher when the $C_{NO}$ condition is greater at identical exhaust temperatures. The oxidation efficiencies of particulate are less than 20% at different $C_{NO}$ conditions at 500 K, and the oxidation efficiencies of particulate are greater than 90% at exhaust temperatures greater than 635 K. This is because that the temperature is low, resulting in a lower rate of oxidation. The catalyst activity gradually increases and the rate of particulate oxidation accelerates as the exhaust temperature increases, resulting in a rapid increase in the rate of particulate oxidation. As the $C_{NO}$ increases, the NO$_2$ concentration at the carrier outlet also increases, resulting in a faster combustion efficiency of particulate in the filter area. As a result, at identical exhaust temperatures, the combustion efficiency of particulate is higher at greater $C_{NO}$. Thus, an appropriate increase in $C_{NO}$ will help to reach a more effective particulate cleaning effect.

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

Thus, an appropriate increase in $P_e$ will help to reach a more effective particulate cleaning effect.

3.3 The distribution pattern of NO mass fraction

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

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

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

4. Orthogonal experiment design and analysis

4.1 Experimental scheme design

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

<table>
<thead>
<tr>
<th>Examples</th>
<th>( v_f )</th>
<th>( C_o )</th>
<th>( C_{NO} )</th>
<th>( P_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16 g/s</td>
<td>1.2%</td>
<td>1000 ppm</td>
<td>0.3 kW</td>
</tr>
<tr>
<td>2</td>
<td>16 g/s</td>
<td>1.6%</td>
<td>800 ppm</td>
<td>0.5 kW</td>
</tr>
<tr>
<td>3</td>
<td>16 g/s</td>
<td>2.0%</td>
<td>600 ppm</td>
<td>0.7 kW</td>
</tr>
<tr>
<td>4</td>
<td>20 g/s</td>
<td>1.2%</td>
<td>800 ppm</td>
<td>0.7 kW</td>
</tr>
<tr>
<td>5</td>
<td>20 g/s</td>
<td>1.6%</td>
<td>600 ppm</td>
<td>0.3 kW</td>
</tr>
<tr>
<td>6</td>
<td>20 g/s</td>
<td>2.0%</td>
<td>1000 ppm</td>
<td>0.5 kW</td>
</tr>
<tr>
<td>7</td>
<td>24 g/s</td>
<td>1.2%</td>
<td>600 ppm</td>
<td>0.5 kW</td>
</tr>
<tr>
<td>8</td>
<td>24 g/s</td>
<td>1.6%</td>
<td>1000 ppm</td>
<td>0.7 kW</td>
</tr>
<tr>
<td>9</td>
<td>24 g/s</td>
<td>2.0%</td>
<td>800 ppm</td>
<td>0.3 kW</td>
</tr>
</tbody>
</table>

4.2 The results of orthogonal experiment

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

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

The average value is 74.8%

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

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

![Fig.12. Range percentage of each influencing factor](image)

4.3 Optimal results

As we can see from Fig. 13, the novel CGPFs can reach a high catalytic efficiency of NO and 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
the $P_e$ is 0.7 kW. The catalytic efficiency of NO is increased by 3.6% and the combustion efficiency of particulate is increased by 16.7% with a 0.2 kW increase in electric heating power compared to the initial condition.

Fig. 13. Comparison of optimal results.

5. Conclusions

Current researches on CGPFs focused primarily on various influence factors such as structural parameters, intake parameters, and different regeneration technologies on the individual catalytic converter and particulate filter interior flow field, pressure drop and regeneration rate. A comprehensive in-depth investigation of the NOx conversion efficiency and particulate combustion efficiency of CGPFs is relatively lacking. Therefore, to enhance the flow uniformity and the NOx
conversion efficiency and particulate combustion efficiency at low exhaust temperature conditions, the physical and mathematical models of a novel CGPFs are proposed based on the computational fluid dynamics software. The influence patterns of different influencing factors on the NOx conversion efficiency and particulate combustion efficiency of CGPFs are investigated. The main findings are as follows:

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

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

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

(4) Properly increasing the heating power $P_e$ is conducive to improving the NOx conversion efficiency and particulate combustion efficiency. The maximal catalytic efficiency of NO is maintained at 62% as the $P_e$ increases from 0.3 kW to 0.7 kW. The combustion efficiency of
particulate is higher while the \( P_e \) is greater at identical exhaust temperatures.

(5) The novel CGPFs can reach a high catalytic efficiency of NO and 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 the \( P_e \) is 0.7 kW. The catalytic efficiency of NO is increased by 3.6\% and the combustion efficiency of particulate is increased by 16.7\% with a 0.2 kW increase in electric heating power compared to the initial condition.

Authors’ contributions


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Data availability

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

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.
Ethical approval and consent to participate

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

Consent for publication

Not applicable.

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