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Abstract

A new method that optimizes the control map of hydrocarbon addition to the diesel exhaust gas for hydrocarbon selective catalyst reduction has been developed. This method is comprised of a numerical HC-DeNOx catalyst model and a new optimization technique using Evolutionary Programming based on the evolution of living organisms. The numerical HC-DeNOx catalyst model was also used to describe HC adsorptiondesorption.¹⁾ As a result of this evaluation, the number of calculations to obtain the optimal control map with this method was less by one

third than that of all maps surveys. By using the obtained optimal control map, the NOx conversion under the Japanese 10-15 mode of the inlet-side heavily Platinum-loaded catalyst was higher by 13% than that of the uniformly Platinum-loaded catalyst in spite of the same amount of the loaded platinum. This was because the heavily platinum-loaded catalyst could start the NOx reduction at a lower temperature, enabling the optimal control map to keep the catalyst temperature within the temperature window of the catalyst for a longer time.

Keywords Diesel engine, Aftertreatment, Optimization, Catalyst, Simulation

選択還元型NOx触媒 (DeNOx catalyst) を用いる 場合必要となる還元剤の添加量,添加タイミング を制御するマップを,効率良く最適化する手法を 考案した。この手法には,触媒反応モデルと最適 化手法として進化的プログラミングを応用した。 触媒反応モデルは炭化水素 (HC)を還元剤とし, 触媒へのHC吸着脱離現象を表現できるモデルを 採用した¹⁾。最適化手法として用いた進化的プロ グラミングは,生物の進化過程を模倣した手法で, 他変数問題や数式化不能な問題などの最適解探索 に有効な手法である。簡略化した添加制御マップ

要

旨

により本手法を評価したところ,全マップ検索に 比べて約1/3の計算回数で最適値を得ることがで きた。本手法を用い,上流側が高白金(Pt)担持な 触媒と均一Pt担持触媒(いずれもPt量は同じ)で, 10-15モードにおけるNOx浄化率を比較したとこ ろ,上流側を高Pt担持にした場合,NOx浄化率を 約13%向上できることが分かった。これは,高Pt 担持により低温から触媒活性が現れたことと,最 適化したHC添加制御により触媒温度を長時間温 度ウインド内に保持できたことによるものであっ た。

キーワード ディーゼルエンジン , 排気浄化 , 最適化 , 触媒 , シミュレーション

1. Introduction

The development of a diesel engine aftertreatment system has recently received great attention. One system uses a DeNOx catalyst with hydrocarbon (HC) as the reductant²⁻⁵) in order to treat NOx, one of many diesel engine pollutants. This DeNOx catalyst system will hereafter be referred to as the HC-DeNOx catalyst system. The HC-DeNOx catalyst system requires an optimal amount of hydrocarbon addition to the inlet gas, because the naturally occurring HC concentration in diesel engine exhaust is too low for sufficient NOx conversion. Thus, hydrocarbons have to be added to the exhaust gas either by post injection using a common rail or by secondary fuel injection in the exhaust manifold. Optimizing the amount of additional HC and the injection timing is key to obtaining a high NOx conversion.

This study aims to develop a new method to optimize the HC addition control map, which determines the quantity and timing of HC injections. The goal is to obtain a high NOx conversion and eliminate wasteful addition of HC. To this end, we developed a numerical model for the HC-DeNOx catalyst and a new optimization technique for seeking the optimal control map. The model used is explained in detail in Ref. 1. In the present study, a two-dimensional map was used to control the addition of HC to the engine exhaust gas. However, the number of maps was so large that it was practically impossible to search through all the possibilities to seek out a map that yielded a high NOx conversion and low amount of additional HC. To be able to carry out the search more efficiently, we employed Evolutionary Programming (EP), an optimization method based on the evolution of living organisms that has been applied to many optimization problems.⁶⁾ We applied the numerical model and EP to the optimization of the HC addition control map for the Japanese 10-15 mode NOx conversion.

2. Optimization method⁶⁾

Evolutionary Programming (EP) is implemented as follows (**Fig. 1**):

I. Set the initial parameters x_i^P , $i = 1, \dots, n$ as a

parent parameters, where n is the number of parameters. The distribution of the initial values is typically uniform.

II. Calculate the solution $S(x^{P})$ to the problem by using the parent parameters.

III. From the parent parameters x_i^P , $i = 1, \dots, n$ create the corresponding offspring parameters x_i^O , $i = 1, \dots, n$ by adding to each x_i^P a Gaussian random variable with a mean of zero and a preselected standard deviation σ .

IV. Calculate the solution $S(x^O)$ to the problem by using the offspring parameters.

V. Compare $S(x^{P})$ with $S(x^{O})$ to select those parameters that yield a better solution. These parameters become the parent parameters of the next generation.

VI. The process of generating new trials and selecting the parameters with the better solution continues until a sufficient solution is obtained or the available computation cycles are exhausted.

In this process, σ was replaced by the better solution according to the rate of appearance of offspring. σ was replaced according to the following rules:

$$\sigma_{k=k+1} = 0.82 \sigma_k \text{ if } Q < 0.2$$
$$= \sigma_k / 0.82 \text{ if } Q > 0.2$$
$$= \sigma_k \text{ if } Q = 0.2$$



Fig. 1 Algorithm of evolutionary programming.

where Q is the rate of replacement of offspring with a better solution, and k is the number of generations. Given the rules for σ replacement, a wide area could be searched while the optimization process was in its beginning stages; the search area was narrowed down as the optimal solution was approached.

3. Experiments

3.1 Survey of number of calculations needed to obtain an optimal map

The suitability of EP was investigated using the engine test data. The control architecture of HC addition to the exhaust gas is shown in Fig. 2. The control map used in accordance with the Japanese 10-15 mode contained 225 parameters, each of which had 5 levels. It was practically impossible to survey all the 5^{225} maps thus created. To minimize the number of maps, a reduced map was used for this evaluation. On the reduced map, the X axis, which represented the gas temperature downstream from the catalyst, had 3 levels, while the Y axis, which represented the gas temperature upstream from the catalyst, had 2 levels (Fig. 3). Each parameter existed in one of 2 levels, namely either 0 or 0.5, yielding 2^6 maps altogether. 0 denoted no HC addition, while 0.5 denoted 1500 ppm C/stroke HC. The engine test data used in this survey was measured as follows:

I. Engine type: 2.2L-IDI

II. Engine speed: 1710 rpm



Fig. 2 Structure of HC addition control.

III. Load: 137 Nm (60 s) and 29 Nm (60 s) were repeated alternately. Thus, the time of single load cycle was 120 s.

IV. Calculation time: 360 s.

The following three methods were compared on the basis of the number of calculations needed to obtain the optimal map:

I. Survey of all maps $(2^6 = 64 \text{ cases})$

II. Conventional method (of optimizing each parameter one by one)

III. EP

3. 2 Effect of Platinum(Pt)-loading pattern on NOx conversion

Figure 4 shows the two types of catalysts used with their different Pt-loading patterns. The normal catalyst was loaded with 2 g/L of Pt. The abbreviation 9-1 denotes a catalyst in which 9 g/L of Pt was loaded in the 1.9-cm-long frontal portion of the inlet, and 1 g/L Pt in the remaining portion. The total amount of Pt-loading in the two types of catalysts was the same.

For EP evaluation, a map comprising the catalyst's inlet and outlet gas temperatures was used. To investigate the effect of Pt-loading patterns on NOx

		Temp. of downstream gas of catalyst (℃)		
		250 300		
Temp. of upstream gas of catalyst (℃)	300 -	0.5	0.5	0
		0	0	0.5

Fig. 3 Example of HC addition control map for surveying the number of calculations for optimization.



Fig. 4 Pt-loading pattern on the catalyst.

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conversion, however, a control map having engine speed and load (HC injection quantity) as its axes was used because it is easy to understand the relation between the transient characteristics of the HC addition control and engine operating conditions.

4. Results and discussion

4. 1 Survey of number of calculations needed to obtain an optimal map

Figure 5 compares three optimization methods based on the number of calculations needed to obtain the optimal map. The method that surveyed all of the maps required 64 calculations, the conventional method required 44, while EP required only 20 calculations.

Optimization programs often do not find the optimal point directly, but rather pick out a "better



Fig. 5 Comparison of the number of calculations for optimization.

point" within a selected area. This point is referred to as a local minimum. Due to the change of σ , EP surveys a wide area during the first stages of optimization, and then narrows down the area to obtain a further optimal map once the optimal solution is approached. Therefore, there is little possibility of picking up a local minimum.

4. 2 Effect of Pt-loading pattern on NOx conversion

Figure 6 shows the optimal maps for both the conventional catalyst (uniform Pt-loading) and the 9-1 catalyst (distributed Pt-loading) for the Japanese 10-15 mode. The shaded region in each map corresponds to the HC addition area for the HC-DeNOx catalyst, and the white area to no HC addition. Figure 6 revealed the following characteristics of HC addition control:

I. Amount of HC addition increases during acceleration.

II. HC addition is stopped during slowdown.

III. Optimal amount of HC is injected during idling.

Figure 7 compares the predicted NOx conversion and HC addition values for the 9-1 and normal catalysts in the Japanese 10-15 mode. These predictions were based on EP. According to Fig. 7, NOx conversion with the 9-1 catalyst was 13% greater than that with the normal catalyst, while the amount of HC addition with the 9-1 catalyst was less than that with the normal catalyst.

Figure 8 shows the calculated temperature at 6.5 mm from the inlet for each catalyst in the range from



Fig. 6 Optimal HC addition control maps of the normal catalyst and the 9-1 catalyst. HC is added at black area and stopped at white area. Thickness of the color means addition quantity of added HC.

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175 s to 325 s in the Japanese 10-15 mode. According to Fig. 8, the temperature of the 9-1 catalyst rose more rapidly compared to the normal catalyst. It is believed that the comparatively large amount of Pt loaded at the inlet of the 9-1 catalyst causes the HC oxidation reaction to start at a lower temperature. The temperatures of the gas and catalyst rise due to the heat released during the reaction. In the 9-1 catalyst, the temperature of the catalyst is higher, and the rates of the HC oxidation and NOx reduction reactions are higher. Furthermore, the catalyst temperature is kept within the temperature window (i.e., the temperature range where the NOx reduction reaction occurs) for a longer time by the optimal map. A high NOx conversion was achievable using the 9-1 catalyst owing to its distributed Pt-loading and the optimal HC addition control map. However, it is still necessary that the HC addition be precisely controlled, otherwise, the 9-1 catalyst temperature may easily overshoot the temperature window, leading to insufficient NOx conversion.

5. Conclusion

A new optimization method consisting of an HC-DeNOx catalyst simulation model and Evolutionary Programming was developed. The method could optimize the HC addition control map for NOx reduction with a fewer number of calculations. The analysis of the optimal HC control map yielded the following characteristics of HC addition:

I. HC is added during acceleration.

II. HC is stopped during slowdown.

III. Optimal amount of HC is injected during idling.

Furthermore, a higher NOx conversion was obtained using a catalyst with heavy Pt-loading near the inlet compared to one where the Pt was uniformly distributed. This is because the former starts the NOx reduction at a lower temperature and its temperature is kept within the temperature window for a longer time by the optimal control map. The optimization technique developed in this study is expected to be applicable to control map optimization involving other reductants, as well as to other multivariable optimization problems.



Fig. 8 Calculated temperature at a point 6.5mm from the inlet of each catalyst and engine speed.



Fig. 7 Comparison of the NOx conversion and HC addition quantity between the normal catalyst and the 9-1 catalyst.

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