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Research article

A fuzzy logic urea dosage controller design for two-cell selective catalytic reduction systems

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ABSTRACT

Diesel engines have dominated in the heavy-duty vehicular and marine power source. However, the induced air pollution is a big problem. As people's awareness of environmental protection increasing, the emission regulations of diesel-engine are becoming more stringent. In order to achieve the emission regulations, the after-treatment system is a necessary choice. Specifically, the selective catalytic reduction (SCR) system has been widely applied to reduce the NO_X emissions of diesel engine. Different from single-cell SCR systems, the two-cell systems have various benefits from the modeling and control perspective. In this paper, the urea dosage controller design for two-cell SCR systems was investigated. Firstly, the two-cell SCR modeling was introduced. Based on the developed model, the design procedure for the fuzzy logic urea dosage controller was well addressed. Secondly, simulations and comparisons were employed via an experimental verification of the whole vehicle simulator. And the results showed that the designed controller simultaneously achieved high NO_X reduction rate and low tail-pipe ammonia slip.

1. Introduction

Due to the superior power performance, better fuel efficiency, and lower greenhouse emissions, diesel engines have attracted much attention. However, diesel engines are featured by higher nitrogen oxides (NO_X) and particular matter (PM) emissions compared with gasoline engine counterparts. Legislative regulations on the diesel-engine emissions from different governments and international organization such as international maritime organization are made. For the purpose of satisfying the more and more stringent NO_X emission regulations, many companies and researchers are striving to reduce the NO_X emissions. One kind of solution is to change the in-cylinder combustion status by using the measures of exhaust gas recirculation (EGR), variable geometry turbo (VGT) or advanced combustion modes [1–3], and so on. It is reported that only optimizing the in-cylinder combustion cannot meet the current NO_X emission regulation of Europe, North America and Asia [4]. And an after-treatment system is a promising choice to deal with the NO_X pollution issue of diesel-engine [5]. Among various choices, the urea-based SCR system has been recognized as the most successful techniques for vehicular diesel-engine [5–8].

In SCR system, the gaseous ammonia is acting as the reductant and the main role is to catalytically convert the NO_X emissions to environment-friendly diatomic nitrogen (N_2) and waters (H_2O) [9]. Theoretically, if the urea dosage is large enough and the exhaust gas temperature is suitable, the NO_X conversion efficiency should be very high. However, when the urea is excessive, it would lead to ammonia slip to the tailpipe. Since the gaseous ammonia is also harmful to human health, tailpipe ammonia slip should be constrained. Therefore, urea dose control is essential and the challenge is how to maintain high efficiency of NO_X reduction and low ammonia slip simultaneously. Many SCR researchers have been involved in the study of spray ammonia control. The different models were used in Refs. [10,11]. In Ref. [10], the authors developed a nonlinear model predictive controller design method for the after-treatment system. Both the diesel engine control and the SCR dosage control were optimized. The purpose is to simultaneously improve the fuel economy and emissions reduction efficiency. However, the data-driven models were used in Ref. [11] for the SCR optimal control. In the example case of the paper, the optimum transient conversion rate of NO_X is

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92.71%, and the optimum transient conversion rate of ammonia is 98.67%. Different controllers were designed according to different control strategies in Refs. [12–15]. The authors in Ref. [12] proposed an advanced control strategy based on an air-assisted volumetric urea dosing system. The proposed method covers both the methods of switching working conditions and flow compensation. It is reported in Ref. [13] that a model-based feedforward controller and the controller can simultaneously deal with the known dynamics of the SCR and disturbances & slowly varying parameters. The artificial neural networks and fuzzy PID controllers for the SCR system equipped on a heavy-duty diesel engine were discussed in Ref. [14]. The authors in Ref. [15] investigated the adaptive model predictive controller of a vehicular SCR system. Some researchers have focused on the cross-sensitive of the NO_X sensor. A NO_X sensor which is cross-sensitive to NH_3 was employed in Refs. [16,17] to construct the closed-loop control law.

For two-cell SCR systems, it has many significant advantages over one-cell SCR systems. Comparing with one-cell SCR systems, two-cell SCR systems' models can reduce the error caused by SCR system internal mixed gas state unevenness. And the two-cell SCR systems models are more flexible in designing the feedback controller. In order to achieve a balance between NO_X conversion efficiency and ammonia leakage rate, it's very valuable to study the control strategy of two-cell SCR systems. Adaptive and robust control strategies of two-cell SCR systems can be seen in Refs. [18] and [19]. Though there are a variety of controller design methods in the literature, most of the control laws for SCR systems are complicated. In addition, the controller design for two-cell SCR systems has not been fully investigated.

To develop a simple but efficient controller for two-cell SCR system, a new controller design method for urea dosage needs to be discussed, which motivates this paper. The SCR system belongs to nonlinear system, there exist unknown nonlinear functions and it's difficult to design the controller without satisfying matching condition. The authors in Ref. [20] discussed adaptive fuzzy control of nonlinear system. T-S fuzzy system with time-varying input delay and output constraints was studied in Ref. [21]. The success of these papers proved the fuzzy logic method can be used to approximate the unknown nonlinear characteristics. So in this paper, fuzzy logic is included in the controller. The standard fuzzy control is chosen to simplify the calculation. Fuzzy control also has the following advantages.

(1) Fuzzy control doesn't need the exact mathematical model of the process;
(2) The robustness of fuzzy control is excellent, and fuzzy control is suitable for solving the nonlinear, strong coupling time-varying and lagging problems in process control;
(3) Fuzzy control has a strong fault tolerance, and it also has the ability to adapt to changes in the dynamic characteristics of controlled objects, changes in environmental characteristics and changes in moving conditions;
(4) The operator is easy to man-machine interface through human natural language, and these fuzzy conditional statements are easily added to the control process.

The existence of these advantages makes this paper choose fuzzy control to control the SCR systems of spray ammonia. This control method is of great significance to improve SCR efficiency and reduce ammonia leakage. In general, this control method belongs to the feedback control and the fuzzy logic is employed to determine the controller law. For two-cell SCR systems, the first cell is use to reduce the NO_X emission and the second cell is used to adsorb the ammonia slip from the first cell. Based on the facts, the inputs for the fuzzy logic controller include inlet NO_X concentration to the SCR, NO_X and ammonia concentrations between two cells and the ammonia slip at the tailpipe. The selection of number and types of MFss is well discussed for our specific application. At the same time, simulations and comparisons are provided to show the effectiveness of proposed method.

The rest of this paper is organized as follow. In section 2, the main SCR operation principle and the modeling of SCR are introduced and adopted. In section 3, the fuzzy logic controller design method is proposed. In section 4, simulation analyses and comparisons are conducted to validate the performance of the designed controller. The stability and adaptability of the designed controller are also proved in this section. In section 5, concluding remarks and the future work are summarized.

2. Fundamentals of SCR systems

2.1. SCR operation principle

A schematic view of SCR operations is shown in Fig. 1. There are mainly three processes in the SCR de-NO_X system [5,22]. In the first step, 32.5% of urea solution is injected into the exhaust pipe which is located before the SCR catalyst. This part mainly includes urea evaporation, urea decomposition and isocyanic acid hydrolyzation [7]. If the exhaust gas temperature is within a suitable range, most of the injected urea solution is transformed to gaseous ammonia. In the second part, the gaseous ammonia inside the SCR catalyst can be adsorbed by the SCR catalyst and the adsorbed ammonia acts as the reductant. In the third part, the adsorbed ammonia catalytically react with gaseous NO_X and the reactions lead to N_2 and H_2O [23].

Since the exhaust gas temperature varies in a relatively large range, the reactions of nitrogen oxides to water and nitrogen are complex. The process of NO_X reduction is divided into three steps: AdBlue to ammonia, ammonia adsorption/desorption, and reduction of gas phase NO_X. The dominating chemical reactions and the corresponding chemical reaction rates are organized and adopted as follows [7,24,25].

2.1.1. AdBlue to ammonia

$$NH_2 - CO - NH_2(liquid) \rightarrow NH_2 - CO - NH_2^* + xH_2O \tag{1}$$

$$NH_2 - CO - NH_2^* \rightarrow NH_3 + HNCO \tag{2}$$

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \tag{3}$$

The AdBlue to ammonia process includes three main reactions: (1) AdBlue evaporation, (2) urea decomposition, (3) isocyanic acid hydrolyzation. The 'x' in reaction (1) depends on the concentration of AdBlue. In general, 'x' takes 6.9. The three reactions are assumed to react completely before the SCR catalyst.

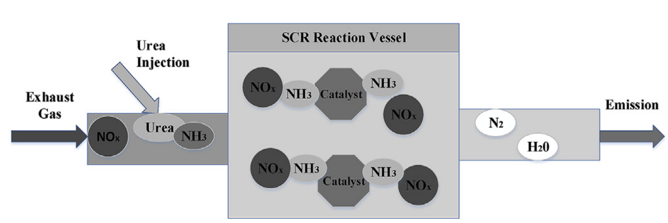

Fig. 1. Schematic diagram of the SCR system.

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