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Control of aged automotive selective catalytic reduction systems for consistent performances

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Abstract

This paper develops a consistent emission control method for automotive selective catalytic reduction (SCR) systems against variant aging conditions. SCR systems have been widely adopted on Diesel vehicles to reduce tailpipe NO_x emissions thanks to their superior performance compared with other aftertreatment technology. While fresh SCRs have a high NO_x removal efficiency, their NO_x reduction performances will be significantly impaired as they get aged. To maintain the consistent emission performance of a SCR system over its entire duty life, it is necessary to design a robust and adaptive control method of SCR against the aging effects and ensure the consistent NO_x reduction capability especially when SCR runs towards its end of life cycle. A control strategy that includes an ammonia coverage ratio tracking controller and a reference generator is derived and validated in simulation environment to account for various SCR aging conditions. The simulation results of US06 test cycle show that the proposed control strategy is able to maintain a consistent emission reduction performance under different aging conditions without generating excessive ammonia slip.

1. Introduction

Lately due to the growing concern of environmental and public health, the NO_x emission from Diesel engine has been regulated strictly by the emission regulatory bodies, including California Air Resource Board (CARB) and Environmental Protection Agency (EPA) [1–3]. Many commercially available aftertreatment approaches have been proposed and implemented

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in ground vehicles to alleviate this issue. Among all available options, selective catalytic reduction (SCR) systems, which relies on ammonia to reduce NO_x through $DeNO_x$ reactions, have been proven much effective and adopted in many applications [4,5]. With that being said, the major challenge is to determine the critical ammonia dosing rate to remove NO_x emission to the most extent with respect to catalyst capability, meanwhile avoiding generating excessive ammonia slip at tailpipe.

The study of model based SCR system control method can be widely found in literature during the past decade [6–12]. It is discovered that ammonia coverage ratio, a key factor that affect both NO_x reduction performance and ammonia slip at same time, has to be regulated to a proper level to meet NO_x as well as ammonia requirement simultaneously. Ammonia coverage ratio is typically driven by external urea injection [7,13]. Due to the time-varying nature of engine and SCR system dynamics and working conditions, a fixed ammonia coverage ratio does not suffice to provide consistent NO_x removal performance under all possible circumstances. Especially after the SCR has served for substantial duty life, the emission performance will deteriorate which result in a decrease of NO_x reduction efficiency and increase of ammonia slip. Such behavior is often referred to as SCR aging effect [14–18]. SCR aging effect is the result of the combination of a series complex factors including catalyst structure and material; exhaust component and temperature, etc. [19,20]. SCR aging will lead to reduction of ammonia storage capacity of SCR system [21]. With the reduction of ammonia storage capacity, available ammonia to take participate in $DeNO_x$ reactions is also limited since NO_x will react with ammonia absorbed by catalyst only [22,23]. In this case, SCR performance will decline and a control strategy adaptively compensating for the loss of ammonia storage capacity is much beneficial to provide admissible emission performance over the whole SCR service life. In an early work of authors [24], we propose a control strategy combining an ammonia coverage ratio tracking controller and a reference generator to compensate for the loss of ammonia storage capacity caused by SCR aging. However, there are two major questions left unanswered in [24]: first the ammonia coverage ratio tracking controller is designed to track a constant target coverage ratio by theory. The controller's converging rate has yet been analytically studied which determines how fast the controller is able to track the desired target; Second the design of ammonia coverage ratio reference in [24] is intuitive and the detail reasoning of such design is lacking. In this paper, we try to answer the above questions in a rigorous fashion and provide with extended simulation studies.

The goal of this study is to develop a control method for SCR system to maintain a consistent NO_x removal and ammonia slip performance regardless of its aging condition. The robust control strategy can be favorable to improve SCR performance particularly with long service time and aged catalyst.

The structure of paper is arranged as follows. The control-oriented SCR model is described briefly in Section II. A SCR control method with explicit consideration of aging effect to provide consistent emission reduction performance is developed in Section III. In Section IV, performance of proposed controller is evaluated and demonstrated under US06 test cycle with simulation results. At last, concluding comments are made at last section.

2. Control oriented SCR model

To develop a control oriented model of SCR, it is assumed that SCR is a continuous stirred tank reactor (CSTR). Compared with monolith reactor model which also takes SCR