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IFAC-PapersOnLine 49-11 (2016) 014–019

Temperature Control of Electrically Heated Catalyst for Cold-start Emission Improvement

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Abstract: Electrically Heated Catalyst (EHC) is a promising technique to reduce the cold-start emission since it enables fast light off for the Three Way Catalytic converter (TWC). In this paper, a composite controller with a Bang-bang Controller and an Active Disturbance Rejection Controller (ADRC) is proposed for the EHC temperature control to reduce cold-start emission. The temperature control includes two different phases: preheating phase (before engine starts) and post-heating phase (after engine starts). The simulation results based on 500 seconds preheating phase and 200 seconds post-heating phase (FTP-75 first 200 seconds) show that the composite controller can have fast tracking performance and small steady-state error.

Keywords: Electrically Heated Catalyst, Light off, Active Disturbance Rejection Controller, Three Way Catalytic converter, Cold-start Emission.

1. INTRODUCTION

Conventional TWC is widely used in gasoline engine since it can achieve a high reduction of CO, HC and NOx at the same time when the air/fuel ratio is close to 14.7 (or lambda is approximately 1). The emission conversion efficiency of conventional TWC highly depends on its wall temperature. It works at a high conversion efficiency only after its wall temperature reaches its light-off temperature. Hence, the engine-out emission is very serious in cold-start phase when the exhaust gas temperature is low. What's worse, improved combustion efficiency and reduced losses have caused exhaust gas temperatures to decrease (Pace et al. (2011)). Proper use of EHC becomes effective way to improve the cold-start emission, with the increasingly strict emission regulation, especially in Plug-in hybrid electric vehicles (PHEVs) and extended-range electric vehicles (EREVs) with frequent stops/starts (Ramanathan et al. (2011)).

It has been reported that the EHC is an effective way to lower fuel consumption and reduce cold-start emission both in diesel engine (Harder et al. (2013); Kim et al. (2012); Pfahl et al. (2012)) and gasoline engine (Pfahl et al. (2012); Charles et al. (2013); Tyagi et al. (2013); Kessels et al. (2010); Presti et al. (2013); Bezaire et al. (2011)). The EHC technology is designed to heat the ceramic-substrate catalytic converter directly or incoming exhaust gas via resistive heating of metal-substrate monolith catalyst mounted ahead of a conventional ceramic-substrate catalytic converter (Ramanathan et al. (2011)). The mathematical modeling and analysis of EHC (Ramanathan et al. (2011)) showed that there exists an optimum electric heater volume for cases with either preheating only or a combination of pre-heating and post-heating. By implementing the preheating method to catalytic converters, the desired amount of control over automotive pollution is achieved in (Charles et al. (2013); Tyagi et al. (2013)). The effectiveness of the EHC and the ignition retard for an integrated powertrain control was compared (Kessels et al. (2010)). To assess the influence on the fuel consumption and tailpipe emission, six different engine-based and EHC-based managing strategies have been tested and compared in (Presti et al. (2013)).

However, the temperature control of EHC is still limited in literature. A feed-forward controller combining PI feedback controller is used in (Bezaire et al. (2011)) to control the temperature of EHC to a constant target and avoid the temperature over a safe threshold.

In this paper, a novel composite controller with a Bang-bang Controller and an ADRC is proposed for the EHC temperature control. The Active Disturbance Rejection Control (ADRC) concept (Gao Z et al. (2001); Han J (2009); Gao Z (2006)) has been widely used in many fields to deal with disturbances and model uncertainties (Zheng Q et al. (2009); Gao Z (2003); Jinbiao Ning et al. (2014)). The contributions of this paper are 1) the fast light-off is treated as a time-optimal control problem through the Bang-bang controller when the tracking error is large. 2) an ADRC is proposed to reject the disturbance when the tracking error is within a certain threshold. 3) the input of the composite controller with a Bang-bang Controller and an ADRC was compared with other control methods and indicated the least frequent switching between upper and lower threshold.

The rest of the paper is organized as follows. A brief introduction of the EHC principle and the EHC model are demonstrated in section II. The composite controller with

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.08.003

a Bang-bang controller and an ADRC design is presented in section III. Simulation results based on 500 seconds preheating and 200 seconds post-heating phase (FTP-75 first 200 seconds) are introduced to verify the proposed approach in section IV. At the end of the paper, conclusion is given.

2. THE THERMAL DYNAMIC AND ORIENTED CONTROL MODEL OF THE EHC

The EHC presented in this paper is a metal-substrate monolith with catalyst coated in it, which means that substrate is not only a conventional TWC substrate but also directly heated by external power source. As can be seen from Fig. 1, to make it simple, the EHC consists of a conventional TWC and a heater, which can heat the TWC substrate directly. There are different strategies to heat the catalyst. The heating event before the engine starts is called preheating phase and the heating event after the engine starts is called post-heating phase. In the preheating phase, there is no exhaust gas into the EHC so that no chemical reactions occur in the substrate. However, in the post-heating phase, there is exhaust gas through the converter and reactions occur. Therefore, there are different thermal dynamics between these two different heating phases.

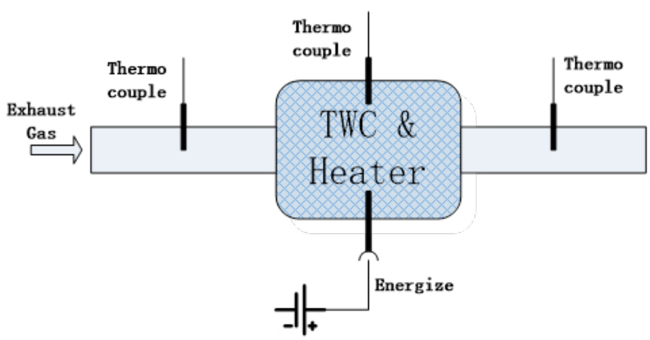

Fig. 1. Stucture of EHC

2.1 Preheating Thermal Dynamic

There is no exhaust gas through the EHC during preheating phase that no chemical reactions and no heat convection to exhaust gas, as can be seen in Fig. 2. Therefore, the solid-phase energy balance is enough to describe the preheating thermal dynamic. Solid-phase energy balance is expressed as (Ramanathan et al. (2011)):

$$cm\frac{dT}{dt} = P(t) + \varepsilon\delta S(T^4 - T_a^4) + h_{air}S(T_a - T) \tag{1}$$

where c is the heat capacity of the monolith heater, m the mass of the EHC, T is the solid phase temperature of the EHC, T_a is the ambient temperature, $P(t)$ is the electrical power source, ε and δ are coefficients of thermal radiation, S is the outer surface of EHC, h_{air} is the convection coefficient between EHC and the ambient environment.

2.2 Post-heating Thermal Dynamic

When there is exhaust gas through the EHC, the chemical reactions occur and heat convection to exhaust gas is very

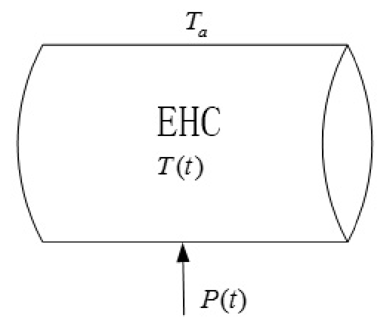

Fig. 2. CSTR model diagram for EHC preheating phase.

significant, as can be seen in Fig. 3. Therefore, the thermal dynamic of EHC includes heat release from reactions, heat exchange with exhaust gas flow and air, thermal radiation, external power source. Therefore, the thermal dynamic of EHC can be expressed by the following equation. Solid-phase energy balance is expressed as (Ramanathan et al. (2011)):

$$cm\frac{dT}{dt} = \sum_{j=1}^{n_{rxn}} a_j(z)(\Delta H)_j R_j + P(t) \\ + h_{gas}S(T_{in} - T) - \varepsilon\delta S(T^4 - T_a^4) + h_{air}S(T_a - T) \tag{2}$$

where h_{gas} represents the convection coefficient between exhaust gas and the EHC, A is the inner surface between exhaust gas and the EHC, T_{in} is the inlet temperature of EHC, ΔH is the enthalpy of the chemical components of exhaust gas, R_j is the reaction rate in the EHC.

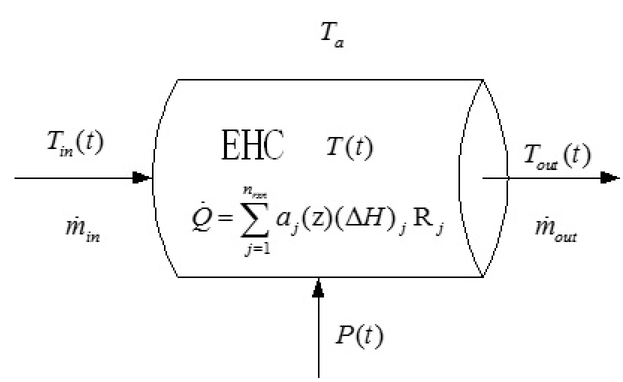

Fig. 3. CSTR model diagram for EHC post-heating phase.

2.3 Main Reactions in EHC

The main reactions in EHC during post-heating phase is demonstrated in table 1.

The reaction rate of reactions (1)-(9) can be expressed:

$$R_i = \frac{k_i C_x C_y \exp(-\frac{E_i}{R_g T})}{G} \tag{3}$$

where i is from 1 to 9. x can be CO, C_3H_6, C_3H_8, H_2, depending on the reactions. y can be O_2, NO, H_2O, depending on the reactions. E is the heat of reaction. R_g is a constant. G is the inhibition factor. The reaction rate