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Controller design and experiment for autothermal reforming of methanol in miniature reactor

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ABSTRACT

In this paper, a miniature methanol fuel processor and its controller design is introduced for onboard hydrogen production. The hydrogen is generated via autothermal reforming of methanol. The control scheme consists of a hydrogen flow rate controller and a reforming temperature controller. To deal with uncertain system dynamics and external disturbance, an adaptive sliding mode control algorithm is adopted as the hydrogen flow rate controller for regulating hydrogen flow rate by manipulating methanol flow rate. Additionally, a high-gain observer is implemented to estimate the unmeasurable system state. The stability of closed-loop system is guaranteed by standard Lyapunov analysis. Furthermore, a variable ratio control law is employed as the reforming temperature controller to achieve steady reforming temperature by adjusting the reforming air flow rate. Finally, the effectiveness of the entire system is testified by experimental means.

1. Introduction

Driven by the increasing concern for the depletion of the traditional energy sources and also the environment pollution caused by them, hydrogen has become a hot research topic as a clean and efficient replacement. In recent years, a lot of researches on miniature hydrogen fuel cells and their applications (e.g. fuel cell vehicles) have been carried out all over the world with numerous achievements obtained [1,2]. The fuel cell vehicles have been proven to be much more efficient than traditional ones run by internal combustion engines, typically with the rate of 45% vs. 16% [1]. Furthermore, since hydrogen fuel cells generate electricity from chemical reaction (isothermal), they do not burn fuel and therefore do not produce pollutants but water. Therefore, hydrogen fuel cell engines are basically emission free.

However, one of the major difficulties preventing the wide utilization of fuel cell systems is the lack of high-density onboard hydrogen storage solutions and the absence of a dense hydrogen distribution infrastructure [2]. To overcome these problems, it is proposed that hydrogen can be produced continuously onboard from liquid hydrocarbons instead [3]. There are a variety of commonly available hydrocarbons such as methane, methanol, propane, butane, gasoline, diesel that can be used as reforming reactants for hydrogen production. Among these hydrocarbons, methanol is considered to be a better candidate compared with other counterparts, thanks to its advantages such as easy storage, high H:C ratio and no C:C ratio [4]. Meanwhile, methanol only requires moderate reforming temperature and does not produce additional sulphur oxides [5]. Moreover, it can be available in large quantities with a price significantly lower than oil price. Thus, a lot of attention has been drawn to hydrogen production via methanol.

Currently, three major thermochemical reforming techniques are available to produce hydrogen from methanol, i.e., steam reforming, catalytic partial oxidation, and autothermal reforming. Among these, autothermal reforming is considered to be the most effective method to produce hydrogen from methanol in such a way that the reaction is self-sustainable and no external heating is required during operating process [6]. Nevertheless, owing to a series of complicated reactions involved, autothermal reforming of methanol can be seen as a nonlinear multi-input multi-output dynamic process. Once integrated into a fuel cell vehicle, fast start-up and frequent hydrogen flow rate load changes will be required, which post challenging control problem. Meanwhile, the reactor will extinguish itself if the reforming temperature is too low, while the catalyst is deactivated at high temperature. Clearly, the inlet flow rates of methanol, water and air should be carefully selected and controlled in order to obtain desired hydrogen flow rate and appropriate reforming temperature. Moreover, uncertainty of model parameters and time delay issues further increase the difficulty in controlling the process [7,8]. Therefore, how to design an effective and robust control scheme has become important in practical applications.

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In the recent decade, some efforts [7,9] have been devoted to this end. In [7], a feed-forward plus feedback control structure was proposed to regulate the process temperature. It was observed that the feedback control failed to achieve acceptable performance when the load changed. Although the feed-forward controller can improve its performance, it was very sensitive to model mismatch. Hence, the authors concluded that advanced control should be applied to solve this problem. In this effort, a nonlinear multivariable predictive controller was introduced later in [9] to regulate the temperature and hydrogen flow. Only simulation results were obtained to demonstrate the feasibility of the controller. In addition, the reference trajectories were determined offline. Alternatively, an adaptive controller was discussed in [8] for autothermal reforming of methanol with acceptable experimental results, but it did not take the reforming temperature into account.

Initially proposed in [10], variable structure control with a sliding mode has been considered as an efficient and robust tool for various dynamic systems with uncertain conditions. The most prominent advantage of sliding mode controller is its insensitiveness to the variation of model parameters and external disturbances. Owing to the above advantages, sliding mode control has been widely utilized in motion control, robotics, process control and other areas [11–13].

Therefore, in this paper, the control problem of miniature fuel processor system for hydrogen production via autothermal reforming of methanol is considered. By adjusting the methanol flow rate, an adaptive sliding mode controller is proposed for regulating the hydrogen flow rate, even in the presence of system uncertainty and external disturbance. In addition, a variable ratio controller is proposed to maintain the steady reforming temperature by manipulating the reforming air flow rate. To verify the performance of the proposed scheme, a number of experimental studies have been conducted. The results substantiate that the control scheme can achieve satisfactory performance without the requirement of explicit modeling step.

This paper is organized as follows. Section 2 introduces the process of methanol reforming and an experimental platform including a miniature methanol fuel processor built for the research. In Section 3, the control scheme is designed for autothermal reforming of methanol. Section 4 focuses on performance of the proposed control strategy. Finally, the conclusions are given in Section 5.

2. Miniature methanol fuel processor

In this section, the autothermal reforming process of methanol is introduced first. Currently, three major methods are available for hydrogen production from methanol: partial oxidation, steam reforming and autothermal reforming [3–5]. On one hand, partial oxidation of methanol:

$$CH_3OH+\tfrac{1}{2}O_2\rightarrow 2H_2+CO_2$$
$$\Delta H^0_{298}=-192.3\ \text{kJ/mol}$$

produces a low concentration of hydrogen. Due to its intense exothermic nature, it is necessary to control the temperature to avoid damaging the catalyst. On the other hand, steam reforming of methanol:

$$CH_3OH+H_2O\rightarrow 3H_2+CO_2$$
$$\Delta H^0_{298}=+49.4\ \text{kJ/mol}$$

is an endothermic reaction which requires additional heat to guarantee the operation of the reaction. It can produce hydrogen with comparatively high concentration. Eventually, based on partial oxidation and steam reforming, autothermal reforming of methanol:

$$CH_3OH+(1-2r)H_2O+rO_2\rightarrow(3-2r)H_2+CO_2$$
$$\Delta H^0_{298}=(50.2-483.6r)\ \text{kJ/mol},\quad 0\le r\le 0.5$$

can reach an approximate thermal equilibrium when methanol, oxygen and water are fed in with an appropriate proportion [3,5]. r is a coefficient that represents the ratio between oxygen and methanol involved in the reaction. Thus, autothermal reforming of methanol is an optimal choice in terms of generating hydrogen with an acceptable concentration without requiring additional heating or cooling devices.

Nowadays, most existing control designs for methanol reforming systems remain in simulation stage. However, in practice, since the actual system is susceptible to external noise and unknown factors, those simulation results may not be replicable in realtime experiments. In order to get a more applicable and validated methanol fuel cell, a miniature chemical experimental platform for hydrogen production via autothermal reforming of methanol is built in our lab as shown in Fig. 1. The pilot platform mainly consists of a miniature fuel processor, a computer, some actuators (including advection pumps, gas flow control valves), measuring transducers (including hydrogen concentration analyzer, gas flow meters, thermocouples) and other necessary peripherals. The core of the platform is the miniature fuel processor, which consists of a micro-structured reformer, a combustor, a two-stage preferential oxidation (PrOx) reactor, some micro-channel heat exchangers, pipes and valves.

To operate the reaction process, appropriate methanol has to be firstly fed into the miniature fuel processor via an advection pump (by Weixing Co., Beijing, China, 2PB00C) as well as the air fed by

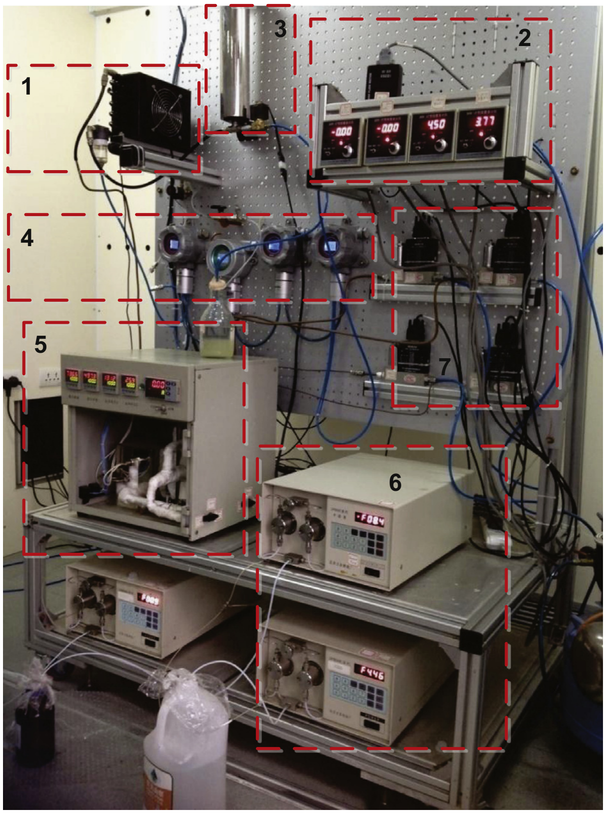

Fig. 1. Experimental platform of the miniature methanol fuel processor: 1 – cooler and gas–liquid separator; 2 – air mass flow controller; 3 – drying tower; 4 – gas composition analyzer; 5 – miniature fuel processor; 6 – advection pump; 7 – air flow control valve.