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Real-time optimization of an industrial steam-methane reformer under distributed sensing

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ABSTRACT

Industrial hydrogen production takes place in large-scale steam methane reformer (SMR) units, whose energy efficiency depends on the interior spatial temperature distribution. In this paper, a control-relevant empirical reduced-order SMR model is presented that predicts the furnace temperature distribution based on fuel input to a group of burners. The model is calibrated using distributed temperature measurements from an array of infrared cameras. The model is employed to optimize in real-time the temperature distribution and increase the energy efficiency in an industrial furnace. Experimental results confirm that the proposed framework has excellent performance.

1. Introduction

Hydrogen (H_2) is a bulk chemical required for manufacturing many important products. For example, it is an essential component of the feedstock for ammonia, methanol, and other commodity chemicals. It is also consumed in large quantities in refineries for processing heavy or sour (high sulfur content) crude oil. Increased demands in these applications mean that demand for hydrogen will continue to rise (Olivieri & Vegliò, 2008). The dominant source of H_2 for such industrial purposes is methane-based steam reforming. The reaction sequence includes endothermic reaction of natural gas (methane) and the exothermic water-gas shift reaction (Eq. (1)):

$$
\begin{aligned}
CH_4(g) + 2H_2O(g) \leftrightarrow 4H_2(g) + CO_2(g), \quad & \triangle H_{298K} = 165\ \text{KJ/mol} \\
CH_4(g) + H_2O(g) \leftrightarrow 3H_2(g) + CO(g), \quad & \triangle H_{298K} = 206\ \text{KJ/mol} \\
CO(g) + H_2O(g) \leftrightarrow CO_2(g) + H_2(g), \quad & \triangle H_{298K} = -41.2\ \text{KJ/mol}
\end{aligned}
\tag{1}
$$

These energy-intensive reactions take place in catalyst-filled tubes placed in a physically large-scale refractory-lined furnace called a steam methane reformer (SMR). Schematic Fig. 1 shows a typical hydrogen manufacturing plant, where synthesis gas product from the SMR passes through a shift reactor followed by product (H_2) separation via pressure swing adsorption (PSA). The SMR unit has two distinct regions (see Fig. 2(a)). The process reactants flow inside the catalyst-packed reformer tubes while the exhaust gases, product of combustion of a mixture of natural gas feed and hydrogen-rich PSA-bed recycle, flow outside the tubes. Energy released through the air-assisted combustion supports the endothermic reforming reactions.

A typical modern hydrogen production plant of capacity 112,000 Nm^3/h (~100 million standard cubic feet per day) of H_2 consumes a substantial amount (~10^5 GJ) of natural gas per day (Peng, 2012). Consequently, the overall energy productivity (energy consumed per unit H_2 produced) of the plant is strongly dependent on how efficiently the SMR is operated. In the spatially-distributed high temperature environment of the furnace, the temperature of the exhaust gas is typically in the ~1300 K range (Murthy & Murthy, 1988). One way to ensure maximum operation efficiency is to process the entire feedstock in the most similar way in order to make uniform products with minimum waste (Van Gerven & Stankiewicz, 2009). This translates to maintaining a uniform spatial tube temperature profile within the furnace. Note that temperature variations along the length, from top to bottom, of a tube are inevitable. However, in an ideal scenario, the axial temperature for every tube is the same, i.e., at a given axial position (furnace height), tube-wall temperatures for all the tubes would be identical. The temperature distribution depends on operating conditions such as the feed flow rate through the reformer tubes, ambient temperature, and fuel and air distribution among the burners, as well as on design of the burners and the fuel and air distribution header. In practice, as reported by Slavejkov, Li, Joshi, Waibel, and Bussman (2006) the discrepancy between the maximum and minimum tube-wall temperatures (TWTs) at a given axial position can be as high as 110 K.

A practical approach for real-time control of the temperature distribution is through manipulation of fuel distribution among the burners. Fig. 3 shows the fuel distribution system where the

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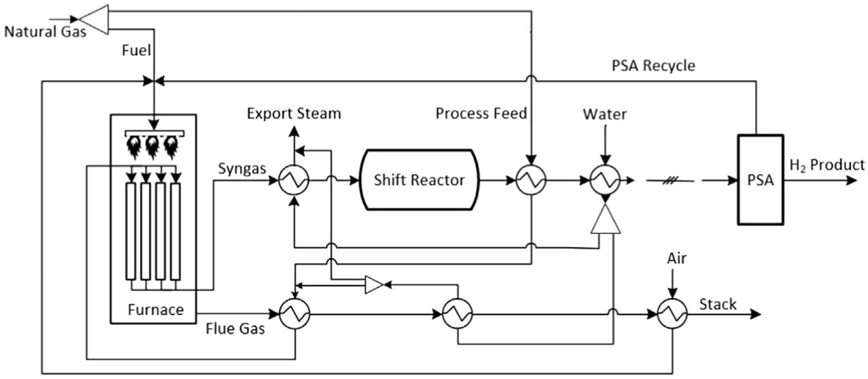

Fig. 1. Schematic of a reforming-based hydrogen production plant (adapted from Esposito & Dadebo, 2011).

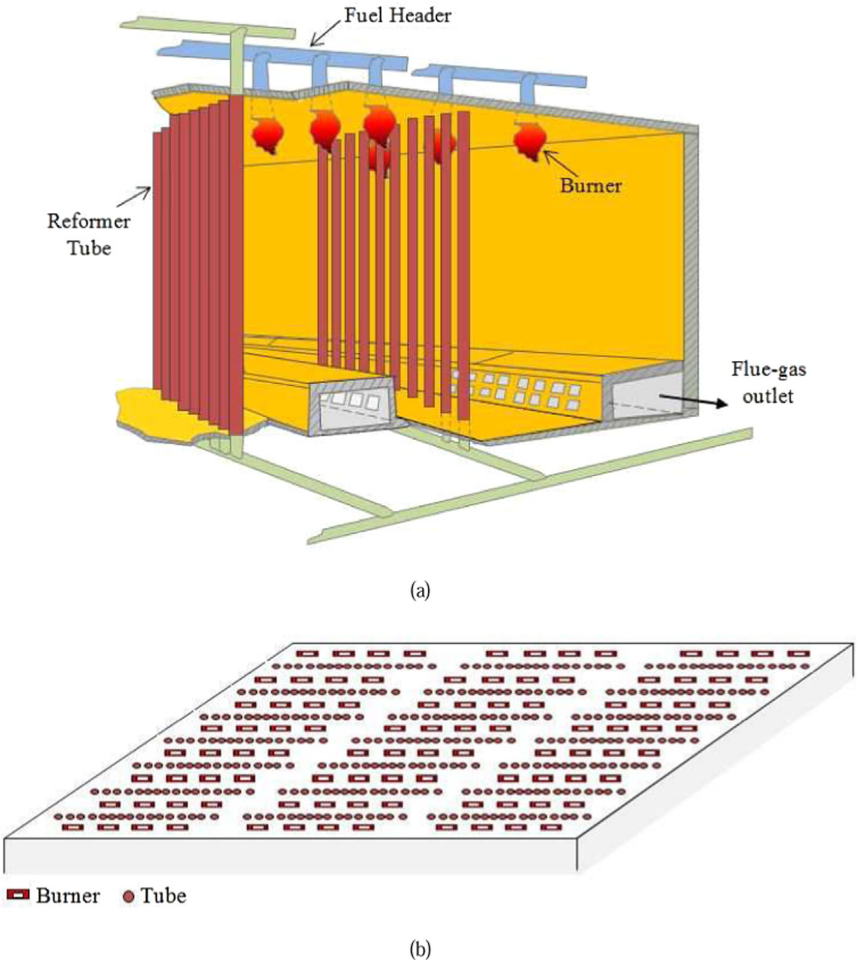

Fig. 2. Schematic of (a) a typical top-fired SMR and (b) top-view showing the arrangements of burners and tubes in the test-bed SMR with 8 and 7 rows of burners and tubes, respectively (adapted from Latham et al., 2011).

burners draw fuel from a fuel header. All the fuel headers supply fuel to burners in their respective rows and are joined to a main inlet fuel header at one end of the furnace. The fuel-line to each burner is typically provided with a manual valve and thus fuel from a burner can be diverted to the other burners by partially closing the valve. However, the TWTs and thus the optimal fuel distribution change due to disturbances that affect the furnace. Thus the fuel distribution needs to be adjusted periodically since there is no unique fuel distribution that is optimal for all operating conditions. This in turn requires a sufficiently accurate furnace model that can predict in real-time the TWT distribution as a function of the fuel distribution or any other manipulated variable that indirectly influences the fuel distribution. Most of the first-principles furnace models (McGreavy & Newmann, 1969; Singh & Saraf, 1979; Murthy & Murthy, 1988; Zamaniyan, Ebrahimi, & Mohammadzadeh, 2008; Olivieri & Vegliò, 2008; Dunn, Yustos, & Mujtaba, 2008; Latham, McAuley, Peppley, & Raybold, 2011) available in the literature do not resolve the complete TWT distribution. Either all the tubes are lumped together to give an average tube temperature, or only the tubes in different radiative environments are modeled separately (Dunn et al., 2008). Consequently, Dunn et al. (2008) carried out partial furnace optimization by adjusting fuel and reactant gas distribution. Apart from tube lumping, several other approximations are made, such as ignoring