Advanced Control of an Onboard Fuel Processor for Fuel Cell Applications

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With the booming population and economy of the world, the issues of global warming and an impending energy crisis have risen to be urgent problems in need of political and scientific solutions. The automotive industry is currently under great pressure to manufacture fuel-saving vehicles with low emission. Among the most promising technologies is the fuel cell. The fuel cell vehicles have proven much more efficient than the traditional vehicles run by internal combustion engines, typically 45% vs. 16% [1]. Another advantage of the fuel cell vehicles is that the greenhouse gas emissions will be zero if the clean fuel, hydrogen is carried onboard.

It is more convenient and efficient to directly store the pure hydrogen fuel as hydrogen. However, due to the expensive hydrogen storage and the safety problems with current technologies, the hydrogen should not be stored at all. Rather, it should be made from natural gas or other fuel using a reformer near the fuel cell as and when it is needed [2]. Currently, a number of researchers have been considering on-board fuel processors that can convert a high energy density fuel (such as gasoline or diesel) into hydrogen which is then passed to the fuel cell. The core of fuel processors is an autothermal reforming (ATR) reactor, which is usually fed by fuel, air and water. Once integrated into a fuel cell vehicle, frequent start-up, shut-down and load changes will be required from the fuel processor. However, such scenarios may fail the ATR reactor because of the tight operating temperature window. The reactor would extinguish if the temperature is low and the high temperature, on the other hand, would burn up the catalyst. Clearly, the feed rates: air and water should be carefully selected and controlled in order to maintain appropriate reactor temperature. Additionally, the well controlled temperature will favor the required hydrogen throughput for the fuel cells and reduce the fuel cost. It is very important to study the dynamics of the ATR reactor and design a robust control system before the fuel processing system can achieve commercial viability.

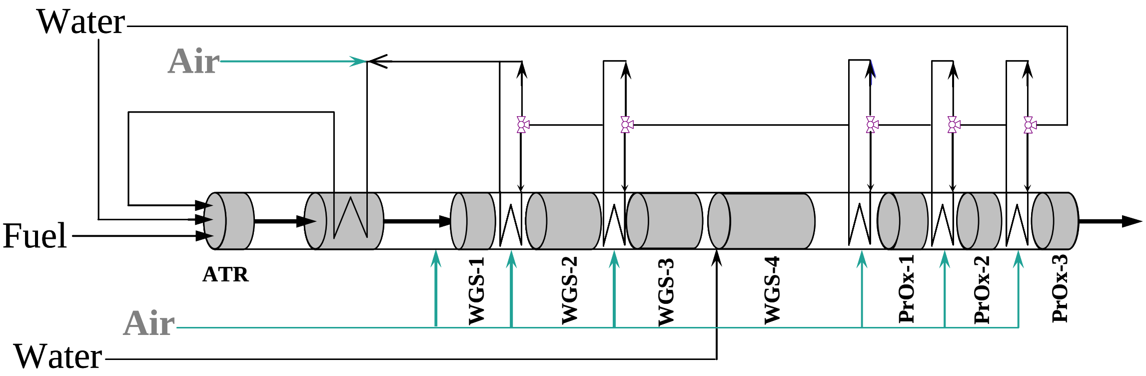

Figure 1 Flow diagram of the FASTER fuel processor

Our research effort is one component of a larger project aimed at identifying the overall start-up capabilities of a fuel processing unit [3]. This project (titled the Feasibility of Acceptable Start-Time Experimental Reformer [FASTER] project) was charged with constructing a 10 kWe system and showing that it could be started in less than 60 seconds.

Additional criteria of the project included size, weight, and efficiency parameters as well as a maximum allocation of energy reactor heating available for the start-up phase. A flow diagram of the constructed FASTER process is depicted in Figure 1. At the heart of the process, we find the ATR reactor.

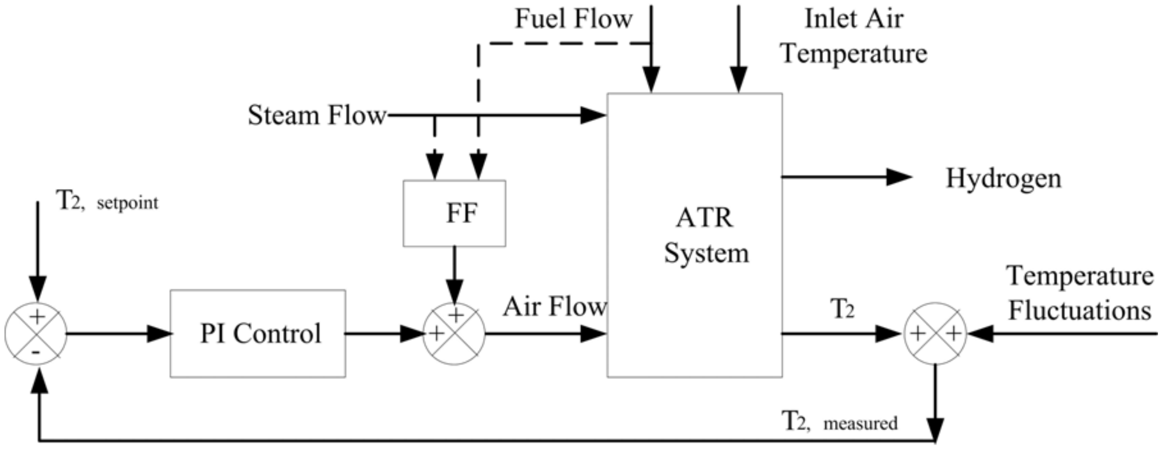

Figure 2 Feed-forward control structure

First, we proposed a feed-forward plus feedback control structure aimed at regulating the temperature of an ATR reactor. In particular, it was found that a classic control scheme is capable of sufficient disturbance attenuation under the assumption of a fixed operating condition. However, during large load changes and the CPOX to ATR mode transition associated with start-up, we found that the feedback only configuration is expected to yield poor performance (mainly due to the large time delay associated with the system’s dynamics). Additionally, it was found that feed-forward control could be used to improve performance during these difficult to control scenarios. It should, however, be noted that the feed-forward controller was quite sensitive to model mismatch and disturbance characteristics. This suggests that performance improvements may be possible by the development of a model based predictive controller, which is capable of incorporating both parameter estimate data as well as disturbance characteristics. The challenge will be to achieve a reactor model with sufficient fidelity while being fast enough for on-line implementation.

To apply advanced control, e.g. model based predictive control to the ATR reactor, we developed a fast dynamic model to predict the dynamics of the ATR reactor within a fuel processor. This model is derived from a Computational Fluid Dynamics (CFD) model, named a reduced order model where the thermal model, originally partial differential equations (PDEs) can be solved analytically by using the lumping procedure and Glerkin approach, and the mass model is reduced from ordinary differential equations (ODEs) to a couple of algebraic equations. The reduced model was compared from simulation data of the CFD model with high precision under CPOX, ATR and Transition modes. The simulations show that although some temperature and concentration profiles don’t match perfectly, but the qualitative agreement is good and the trends of the transient responses can still be captured for a variety of operations which stay within specific operating domains. The computational time of the reduced model has been reduced from 130 s to only 0.04 s for a simulation horizon, 180 s. As a kinetic model, the reduced model has proved to be very fast without sacrificing precision, which will make it possible to apply model predictive control and optimization on line.

Before developing the model predictive control, we also developed a fast procedure to optimize the operating conditions for the desired hydrogen yield, thus minimize the fuel cost. The process optimization problem is aimed at minimizing the fuel flow in order to reduce the hydrogen production cost for required hydrogen yield. The optimized variables include air flow, steam flow and fuel flow and the process constraints involve flow rate bounds and temperature bounds. With the assumption of only the temperature constraint which is active, we find the fast and analytical solutions for the nonlinear programming problem (see table 1), which will be the targets for the flow controllers.

Table 1 Optimized feed rates for different hydrogen yields

H_2 yield, *mol/min*	T^l, °C	Fuel, *g/min*	Air, *dm^3/min*	Water, *g/min*	O_2/C (R_1)	H_2O/C (R_2)	Net H_2 yield*, %
3	800	27.8	124.2	119.3	0.54	3.33	78.9
	750	26.1	111.3	120.9	0.51	3.59	82.0
5	800	46.3	207	198.8	0.54	3.33	78.9
	750	43.5	185.5	201.5	0.51	3.59	82.0
8	800	74.2	331.3	318.1	0.54	3.33	78.9
	750	69.6	296.8	322.5	0.51	3.59	82.0
10	800	92.7	414.1	397.6	0.54	3.33	78.9
	750	87.0	371.0	403.1	0.51	3.59	82.0

***** The net H_2 yield is defined by the ratio of H_2 yield to the maximum theoretical H_2 yield when the resultants include only carbon dioxide and hydrogen.

Based on the fast dyanmic model develped and the optimized operating conditions, we proposed the nonlinear model based predictive control as shown in Figure 3.

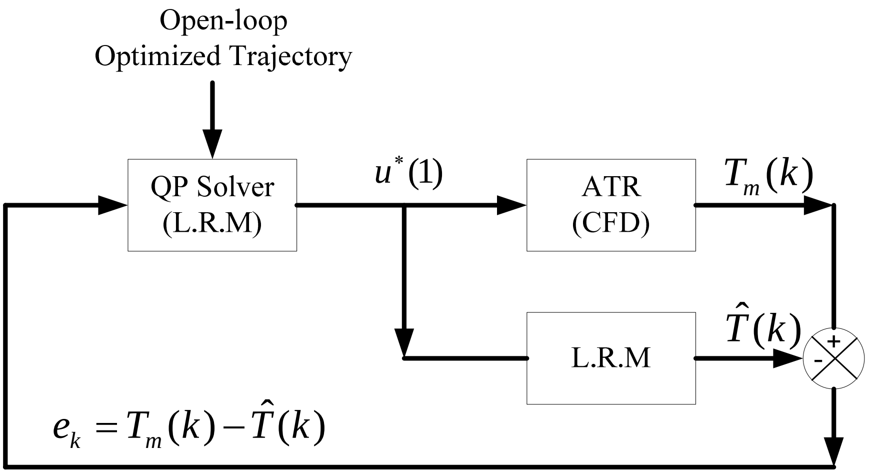

Figure 3 Model Predictive Control for ATR system

L.R.M represents the linear reduced model which is derived around the optimized trajectories of the manipulated variable, air flow and the target temperature. The trajectories are derived from a nonlinear programing problem. The mathematical description for this advanced control is given by

$$\begin{aligned} &\min_{\{y,u\}} J = y^T Q y + u^T R u \\ &s.t. \quad x_{k+1} = A_k x_k + B_k u_k + d_k \\ &\qquad\; y_k = c x_k + e_k \\ &\qquad\; y^l \le y_k \le y^u \\ &\qquad\; u^l \le u_k \le u^u \end{aligned} \qquad \begin{aligned} &y = [y_1\; y_2 \cdots y_p]^T \\ &u = [u_0\; u_1 \cdots u_{q-1}]^T \\ &y_k = T_k - T_k^r, \quad k = 1, \cdots p \\ &u_k = F_{air}(k) - F_{air}^r(k) \\ &k = 0, \cdots q-1 \\ &u_k = u_{q-1}, \quad \forall\, q \le k \le p-1 \end{aligned}$$

The above quadratic programming problem can be solved by numerous solvers but the computational cost is so high that all computation can't be completed with the sample time, typically 0.25 s. Because the input and output constraints had been considered during solving the trajectories, it is reasonable to solve an unconstrained quadratic programming problem, which leads to the following analytic solutions:

$$u^* = K \cdot L_2$$

$$K = -(L_1^T Q L_1 + R)^{-1} L_1^T Q \quad L_1 = C A^{-1} B \quad L_2 = C A^{-1} d + e$$

The simulations show that such a nonlinear model predictive control works very well for an onboard fuel processor, as shown in Figure 4.

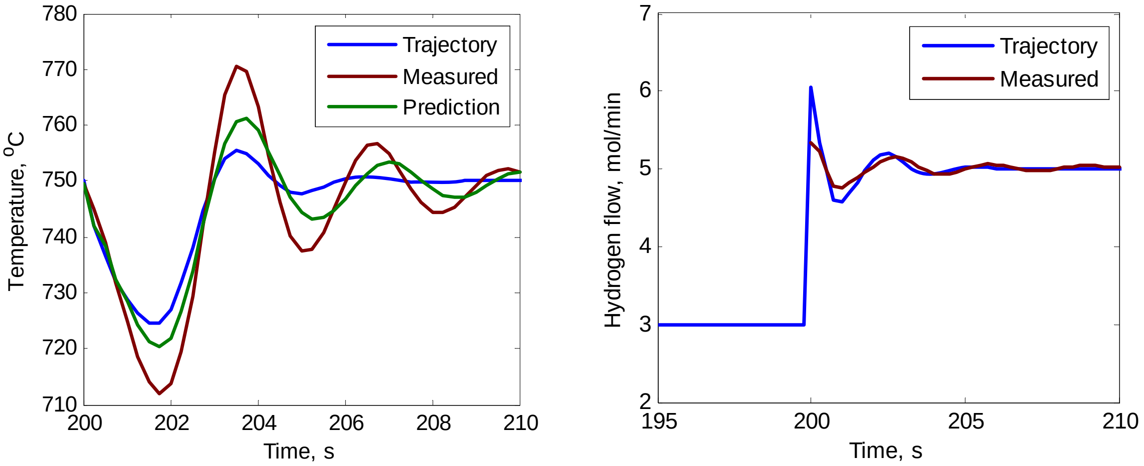

Figure 4 Temperature and hydrogen dynamics for the ATR system with nonlinear MPC

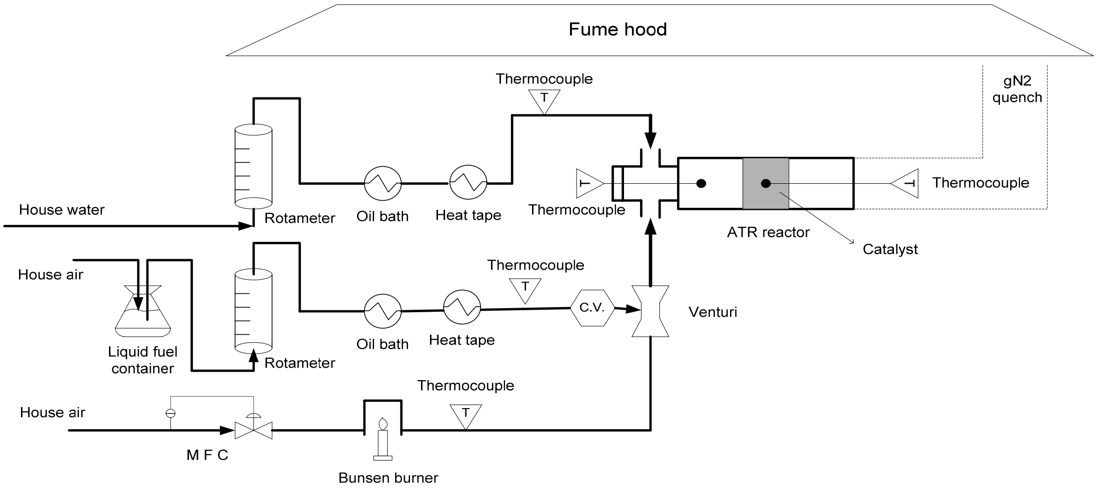

Figure 5 Experimental setup for ATR system

We are currently setting up an ATR apparatus at IIT to validate our advanced control system developed. The experimental flowsheet is shown in figure 5. Liquid water at ambient temperature will be preheated by an oil bath to produce steam at 160 ºC, and then super-heated by a section of heat tape to reach the desired temperature of ~250 ºC. The liquid fuel, octane in our experiment, will be also preheated by an oil bath to produce vaporized fuel, which is also super-heated. This fuel is then mixed with the air stream whose flow rate is electronically manipulated via a mass flow controller and heated to ~400 ºC by a Bunsen burner. Finally the mixture of octane and air will meet with steam at the inlet of ATR reactor. After the reactant gases are fully mixed and the fluid is fully developed, the gases will pass through the catalyst bed and react. The resultant gases will be directly emitted to the fume hood. All thermocouple data will be read by LabVIEW, which will also serve as the feedback link, by sending commands to the mass flow controller of the air stream. The MPC code once developed will be loaded on to the computer via a real-time script function made available by LabVIEW. It is noted that the steam and fuel stream flow rates can only be adjusted manually. To overcome this lack of hardware issue we will simulate a measurement of these disturbances by following a predefined trajectory for each and communicating these trajectories to the NMPC for each experimental run.

Reference

[1] Benefits of Fuel Cells in Transportation, www.fuelcells.org

[2] James Larminie and Andrew Dicks, Fuel Cell Systems Explained, 2nd Edition, 2003, John Wiley & Sons Ltd, England.

[3] S. Ahmed, R. Ahluwalia, S.H.D. Lee, S. Lottes, A gasoline fuel processor designed to study quick-start performance, J. Power Sources, 9(2006), 214.