Multivariable Model Predictive Control (MVMPC) Implementation in an Amine Unit of a Syngas (Hydrogen + CO) Plant

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Introduction

An HyCO plant producing Hydrogen (H_2) and Carbon Monoxide (CO), often by design, contains a CO_2 removal system commonly known as Amine system. Application of an MVMPC in a HyCO plant is not new, however, it is not as common as in the case of distillation columns and many other refinery units. One of the major tasks involved in implementing a Multivariable Model Predictive Control (MVMPC) to any new process is to justify the choice from both technical and economical perspective. On the technical side, after careful evaluations, it was very easy to justify the use of MVMPC for various multivariable control problems in the plant. When economical returns were analyzed, one of the many units in our HyCO plants that immediately attracted the attention of our control engineers is the Amine system.

The amine unit in one of our HyCO plant has been constantly a major bottleneck in the day-to-day operations. Operators often tends to address the operational issues with their individual control strategies due to different levels of experience with the same unit. In the absence of any immediate consequences, the difference in the operating style among the operators is hard to regulate, although the production management team considered such a regulation to be of high value in long term. The reason for envisioning such a long term benefit could be easily attributed to the fact that the plant has experienced very high level of corrosion in the past that reduced the life-time of the column packing almost by half of its original estimated life time.

The MVMPC software used in this application is GMaxC® from Intelligent Optimization Group from Houston, TX. Although we start this implementation with the amine system, our final objective is to implement MVMPC for all the units in the plant.

The following flow diagram (Figure -1) represents various units typically present in a HyCO plant. The main reactor, commonly known as reformer (in this case, Steam-Methane Reformer / SMR) takes natural gas (NG, containing methane) and steam as inputs to produce hydrogen (H_2) and carbon monoxide (CO). The reaction also produces CO_2 which needs to be recycled for improving the CO yield, which is one of the reason for removal of CO_2 from the processed gas from the SMR. The CO_2 free process gas is passed through a drier for removal of moisture and any traces of CO_2 that was not removed in the Amine system. The process gas then enters a membrane system for regulation of H_2:CO ratio before it is sent to the cold box, where the CO is produced with very high purity before it leaves the battery limit for the customer. Pressure Swing Adsorption (PSA) system is used for hydrogen production which can take impure hydrogen from the cold box as input to produce hydrogen of very high purity.

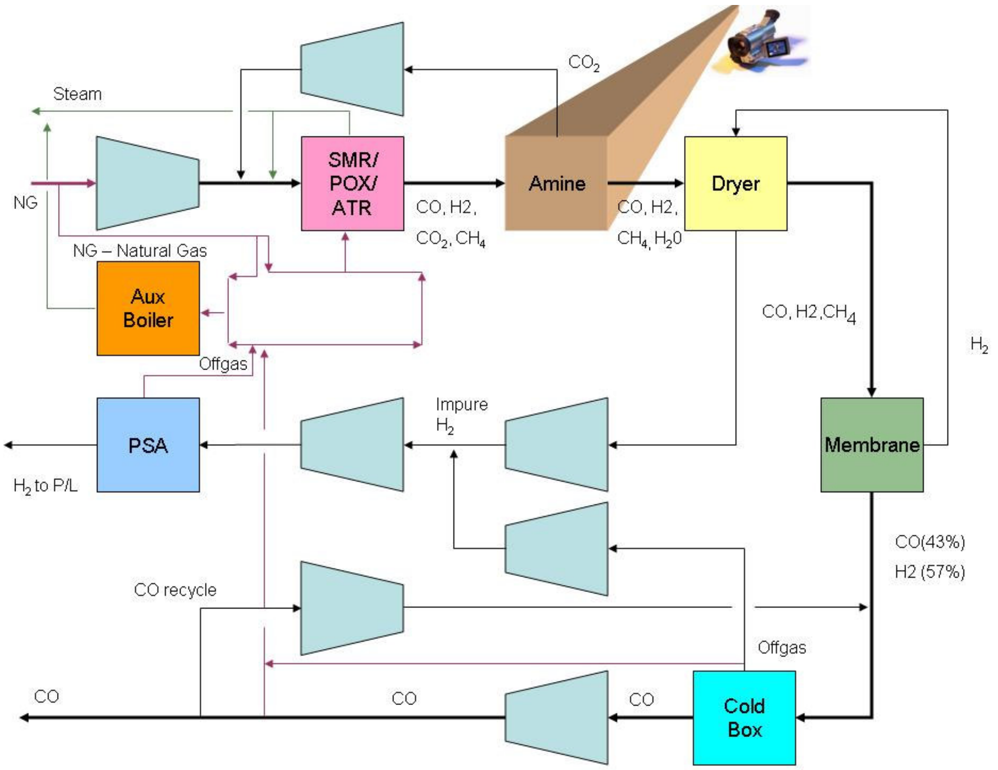

Figure 1: Flow Diagram of a typical HyCO Plant

Literature Review

A most comprehensive article on corrosion in alkanolamine plants was published by Rooney and DuPart (2000) which contains 52 references including books and articles. Based on the researches by Chakma and Meisen (1985) the recommendation for the maximum allowed reboiler temperature is 248^{o} F to avoid any degradation of the amine solution, which is also used as a guideline in our control implementation. Discussion on various material of construction and their corrosion levels when in contact with the amine solution is also available from Rooney and Dupart (2000). The role of filtration and the role of other chemical constituents in the amine solution in view of corrosion are particularly discussed in detail in the same article. Although there are many interesting insights on the corrosion problem in the same article, the most pertinent information available is about monitoring corrosion. This is of particular interest for controller implementation as methods on measurement of the improvements needs to be well established ahead of implementation. In principle, Fe, Cr, and Ni concentration can be used to measure the corrosion, however, Fe levels do not provide reliable way to indicate active corrosion (Rooney and Dupart, 2000). The reason is the formation of FeS, $FeCO_3$, and iron hydroxides, which are often noticed by their deposition in various equipments of the amine system. Based on this information, we decided to use Chromium concentration for measuring active corrosion in the amine system before and after the controller implementation.

Process Description: Amine System

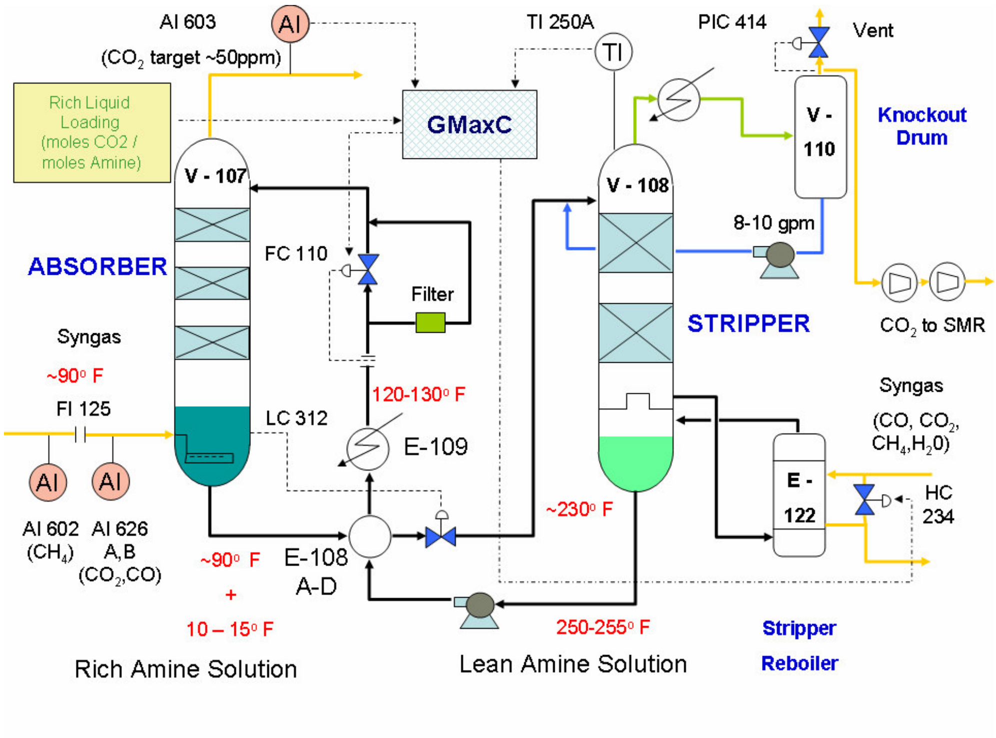

Figure 2: Flow diagram of an Amine Unit

The process gas from SMR containing CO_2 first enters an absorber, where the amine solution at ~120^o F contacts the gas at a temperature of ~90^o F and at a pressure of 350 psi. The physical absorption phenomena remove the CO_2 leaving the process gas with < 50ppm of CO_2 concentration. The absorbed CO_2 rich solution enters the stripper driven by a high pressure differential (120 psi in the stripper) and the stripper is maintained at a high temperature close to 250^o F. In our case, the heating medium for the re-boiler of the stripper is the process gas (part of energy recovery system design). After the release of CO_2 in the stripper, the CO_2 lean amine solution is pumped back to the absorber via heat exchangers for temperature reduction.

Control Problem

The amine system of the HyCO plant considered in this project has two variables that can be adjusted for regulatory purposes. They are (1) the heat input to the re-boiler of the stripper and (2) the recirculation flow of the lean amine solution from the stripper to the absorber. The objective of the new controller is to adjust these two variables so that the plant operational objectives are achieved subjected to the design, safety, and valve constraints. The main operational objectives includes (1) maintenance of CO_2 slip in the process gas stream close to 50 ppm, (2) maintenance of the temperature of the stripper at a minimum feasible point, and (3) maintenance of the temperature variations free from any abrupt change in magnitude. The constraints include (1) maintenance of pressure drop in the absorber column below a specified value, (2) maintenance of pressure drop in top and bottom portion of the stripper column below a specified value, and (3) maintenance of the CO_2 loading (moles of CO_2/unit volume of the active amine solution in the system) below an allowable maximum limit.

Amine System Optimization

Previously, Mooi, A. (2004) from Air Liquide studied another Amine system in one of our plants in Europe and successfully optimized from operational perspective which resulted in notable improvements with significant cost savings. The study was driven by two major motives: (1) To enhance the capacity of the Amine system so as to remove the production bottleneck and (2) To reduce energy consumption in the Amine system as energy from steam (the reboiler heating medium in the plant) was a direct cost to the production. The study focused on altering various parameters of the Amine system and analyzing them in combination with changes in production rates and steam to carbon ratio (a normalized ratio of Steam to NG flow). The objective here was to understand the impact of such changes in the residual CO_2 concentration in the outlet gas from the stripper. The additional parameter monitored in this study include the CO concentration in the amine liquor (both in the CO_2 Lean and Rich Solution) as it has significant contribution in corrosion. One of the suggestion that came out of this study was to increase the size of heat exchangers in the amine system for an improved capacity. The study also brought forth a set of detailed guidelines in terms of various temperatures including the lean amine temperature from the stripper to the absorber for various plant loads. The optimal recirculation flow rates of the amine solution were also established based on this study. Upon implementation, the energy usage reduced from 2.02 to 1.79 BTU/lb CO_2.

For the extension of this study to another plant, the requirement is clearly to repeat this study in the new plant which demands for a dedicated experimentation on the system over an extended period of 6 months. Note that the stripper temperature which is mainly focused in our work has direct correlation with the energy input and hence indirectly optimize the energy usage too. Hence, the control framework that minimizes the temperature while satisfying all the operational requirements would naturally reduce the energy consumption in an Amine Unit. Based on this conclusion, an MVMPC solution was suggested (as a general solution for AL Amine system control) and implemented for the plant under study for which the corrosion problem is the key issue. Our future plan includes transferring the control framework to other plants including the European plant mentioned above.

Which Temperature to Choose for Control?

In the operation of the stripper, there is only one possibility to alter the heat input which is by varying the flow of the (hot) process gas into the re-boiler. However, the temperature measurements that are affected by varying the heat input are (1) the outlet temperature of the amine solution coming out of the reboiler (2) the stripper bottom liquor solution temperature and (3) the overhead vapor temperature of the stripper. All three variables show different dynamics and the challenge is to choose the right one for better modeling and control.

Since the stripper liquid level control (at the bottom) is an independent control not included in the scope of the proposed MVMPC, the bottom temperature variations due to make up water is an additional complication to be considered with choice no. 2. Due to this reason, the bottom temperature was not chosen to be the controlled variable. Based on the flow rate of amine through the reboiler (which is not accurately controlled), the temperature setpoint requirement of the amine stream flowing out of the reboiler may vary for the same energy requirement in the stripper which, when ignored, can lead to unwanted effects even during a stable operation. With the confirmation from the plant engineers and experts, the overhead temperature was chosen to be the representative controlled variable among all three choices.

Control Framework and Modeling

With the Lean amine recirculation flow and the heat input in the reboiler as two manipulated variables(MVs), an MVMP controller was designed for the controlled variables (CVs) that includes CO_2 slip and the stripper overhead temperature with constraints on differential pressures in the absorber and stripper columns. An additional important constraint included in the control framework was the rich liquid loading (total CO_2 entering the system / unit quantity of the amine solution in the system).

One of the major difficultly involved the implementation of the MVMPC control in the amine system is the system modeling. From basic understanding of the system, the system was expected to show some nonlinearity and the model mismatch due to linear assumption was expected to be handled using the feedback capability of the controller. When a series of step changes were introduced in the heat input and recirculation flow, the step changes that resulted in significant and distinct responses were alone chosen for modeling. This means that few unexpected behavior of the system during testing may be noticed (e.g., no response to certain moves). However, such occasional behavior can be safely assumed to have originated from disturbances that are not serious to be considered for MVMPC modeling. First order plus dead time models were identified for the responses and fed into the controller.

Results

When commissioned, immediately the controller started producing good results after minor tuning. However, when left online for a few weeks, operators started complaining about the controller often tends to cool the system too much causing occasional run-away situation causing the excessive residual CO_2 in the process gas coming out of the Amine system. Since the controller was designed to minimize the stripper overhead temperature at all times, specification of the lower bound on the temperature was found to be critical in determining the stability of the controller for a constant MVPMPC tuning parameters. After few months of operation, an optimization strategy that involves determining the lower bound of the stripper overhead temperature for various operating conditions was set and currently being implemented manually. Since, this manual operation occurs at a very low frequency (some times once a week), it is acceptable at the current setup. This part will be automated using a real-time optimizer framework when a plant-wide control is implemented with all the units in this HyCO plant are in control with the MVMPC.

Figure-2 shows the improvement in the stripper overhead temperature after the MVMPC implementation. In the depicted time range shown, no major changes in the operations or equipments were made other than MVMPC implementation. Some of the spikes showing temperature drop below 194^{o} F were artificial caused by the cooling effect of the thermo-well induced by strong wind. It is also to be noted that the pipe-line where this temperature measured is not insulated. The real stripper overhead temperature peak to peak variation has reduced from 10° F to 4° F. The mean temperature has also gone down significantly. (~4° F)

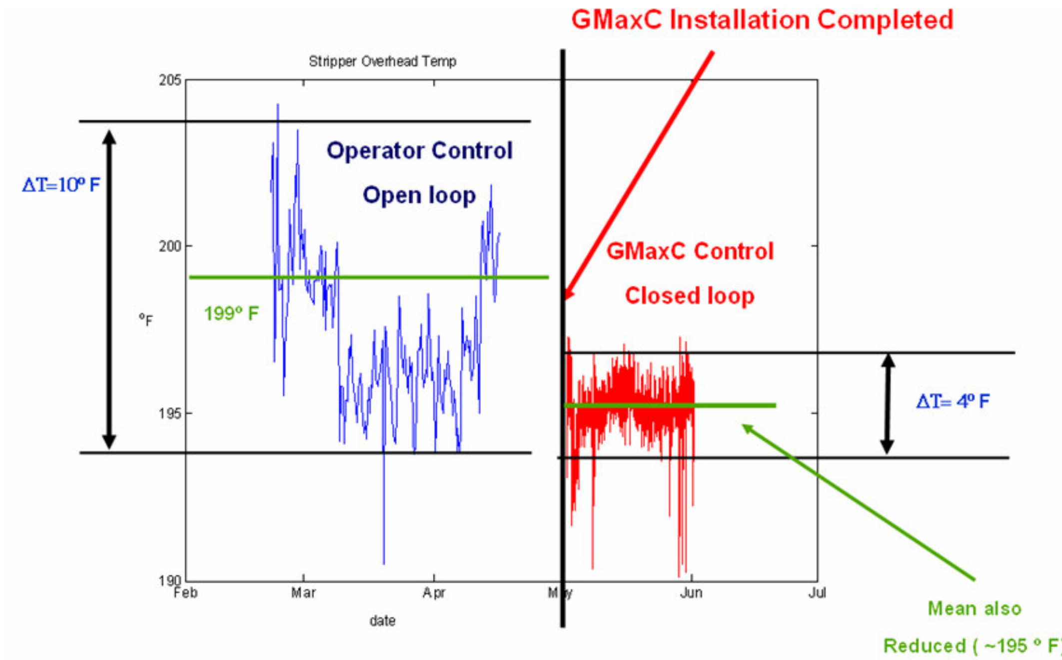

Figure 3: Improvement in stripper overhead temperature after MVMPC implmentation

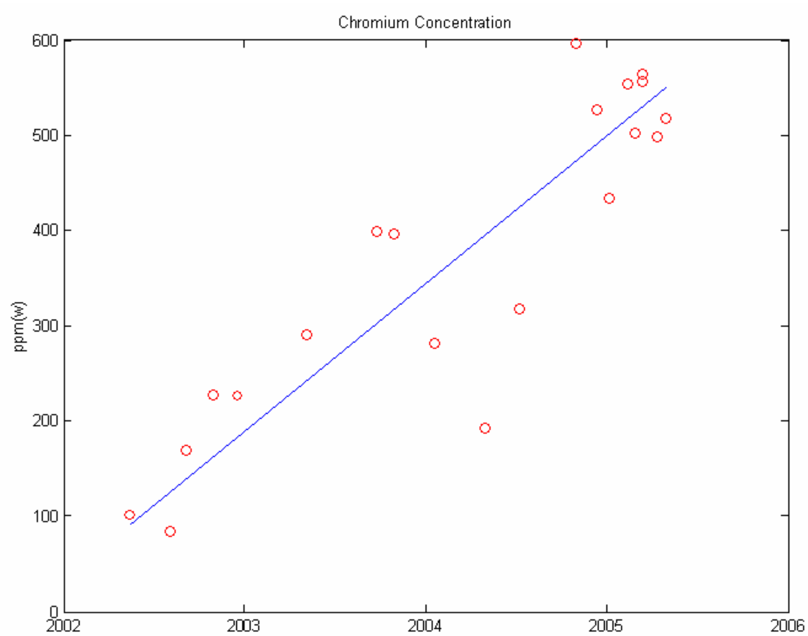

Figure 4 Chromium concentration steady increase from 2002 to 2005

The performance was also monitored with Cr concentration over a long period and the results are shown in Figure-5. Figure-4 shows the chromium concentration in the past when the corrosion problems were experienced to be significantly high. Comparing Figure-4 and Figure-5, the improvements are easily noticeable. Note that the chromium concentration has gone down from ~160 ppm to ~50 ppm. Although not completely reliable as mentioned in the earlier parts of this paper, it is interesting to note that Iron concentration also exhibits reduction trend similar to Chromium concentration.

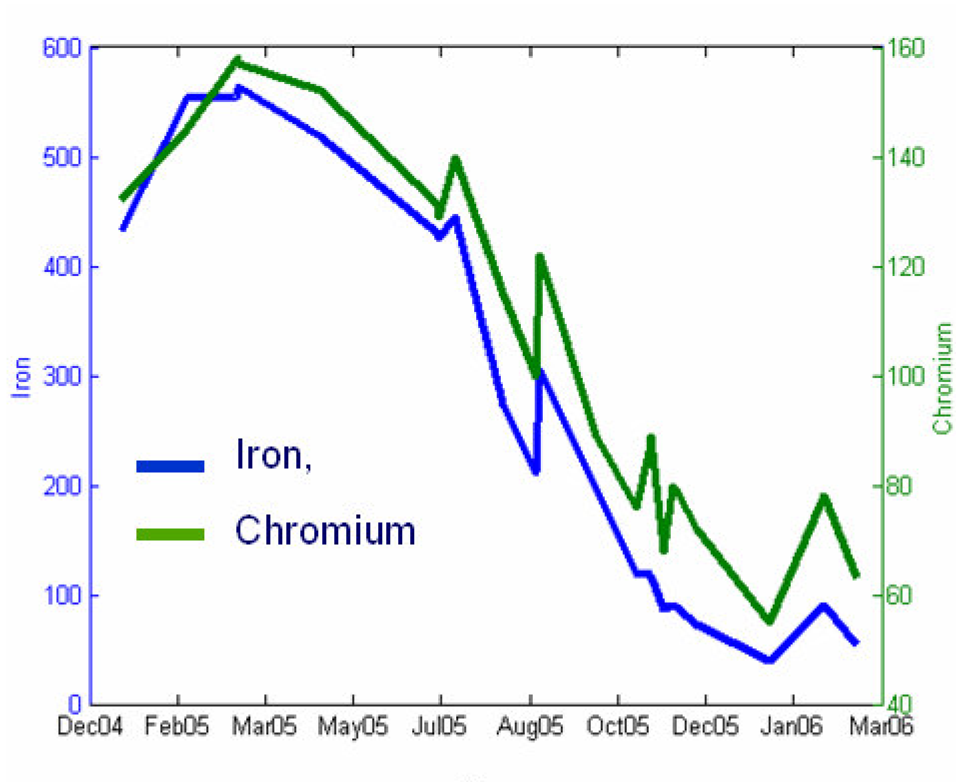

Figure 5: Corrosion reduction indicated by chromium concentration (and Fe concentration)

Conclusion

The MVMPC control implementation has significantly helped addressing the corrosion problem in the amine system. The controller performs very well in controlling the CO_2 slip and stripper temperature minimization, however, the pressure drop in the stripper appears to be slowly increasing over time due to the gradual accumulation of foaming tendency. This necessitates occasional load of antifoam agent into the system. The new controller has helped reducing the operator intervention to a large extent, thus enabling the operator to concentrate on more serious issues in other units. This has improved the operator trust on the controller significantly, which is one of the key requirements for an advanced controller implementation to be successful. In continuation with this implementation, the other parts of the HyCO plant are also being analyzed for MVMPC implementation with the final objective of a plant-wide control.

Acknowledgement

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