IMPLEMENTATION OF INTERNAL MODEL CONTROL (IMC) IN CONTINUOUS DISTILLATION COLUMN

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ABSTRACT

Distillation columns have been widely used in chemical plants for separation process. The high nonlinearity and dynamic behavior of the column make them hard to control. Internal Model Control (IMC) is one of the model based control strategy that have become the central of research to control such column. This paper will review the implementation of IMC in controlling continuous distillation column for the past 28 years. The type of models used as internal models in the IMC is reviewed and highlighted. In addition, the past implementation of IMC weather in simulation based or real application is also reviewed. Based on the review, it is found that many implementations of IMC in the continuous distillation column were based on linear model, using binary components distillation system and tested in the simulation environment. Thus, the implementation of nonlinear based IMC using multi components distillation system is still open for research. Furthermore, the successful of the real time application for such control algorithm also need to be proved.

Keywords: Internal Model Control (IMC); Continuous Distillation; Review

1. INTRODUCTION

Distillation column is one of the important units in chemical process plant. It is estimated that 95 percent of the separation processes for the refining and chemical industries in the world is using distillation column [Enagandula and Riggs, 2006]. Its efficient and robust control is essential in order to achieve the desired product purity within the minimum cost. However, attaining a robust distillation column control is a challenging task due to nonlinearities of the process, multivariable interaction, non stationary behavior and severity of disturbances in the column [Hurowitz *et al*., 2003]. In addition, continuous distillation system can exhibit more dynamic behaviors as the process runs throughout the time.

In order to control the distillation column, the Proportional Integral Derivative (PID) control has been used due to its simplicity design and its performance characteristics [Su *et al*., 2005]. However, the drawback of PID is its control action obviously not based on a process model. Thus, the PID control action did not compensate for the process dynamic knowledge such as dead time and nonlinearity which give it some difficulty in controlling such dynamic process [Bequette, 1991]. The performance of the control system in the distillation control is essential as the distillate product will be directly affected by the controller action. A robust control of distillation will provide a better product quality and reduce waste thus increase the profitability. The advancement of technology in control had

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led to the emerging of more robust control system such as model based control (MBC) strategies including process model based control (PMBC) [Krivosheev and Torgashov, 2001], nonlinear internal model control (NLIMC) [Venkateswarlu and Gangiah, 1997], nonlinear model predictive control (NLMPC) [Kawathekar and Riggs, 2007] and nonlinear inferential control (NLIC) [Doyle, 1998].

Among the MBC techniques, IMC has drawn a great interest to be implemented for the unstable process due to its effectiveness design principle [Shamsuzzoha and Lee, 2008]. IMC also have shown to be more robust when compared to the conventional controller and renowned for its setpoint tracking capabilities [Fieg *et al*., 1996; Marlin, 2000]. The IMC philosophy is based on the Internal Model Principle which states that the control can only be achieved by using the model that able to represent the control system. By using such model, IMC is capable to predict the output constraint violations and take a corrective action [Garcia and Morari, 1982]. Furthermore, IMC control objective is similar to classical feedback control making it simple to be understood by the operators. Besides that, another advantage of IMC are its stability is only depend on the controller and the nominal plant [Morari and Zafiriou, 1989].

2. INTERNAL MODEL CONTROL (IMC)

The development of IMC had begun since the late 1950s in order to design an optimal feedback controller. The first to utilize the structure of a model parallel to the process is Frank in 1974 [Brosilow and Joseph, 2002]. Then, Gracia and Morari [1982 & 1985] had introduced the IMC structure with distinct theoretical framework and application in a multivariable system. The IMC consists of three parts [Garcia and Morari, 1982]: (1) Internal Model: to predict the process response in an attempt to adjust the manipulated variable to achieve control objective; (2) Filter: to achieve certain robustness in controller design; (3) Control algorithm: to calculate the future values of manipulated variable so that the process output is within the desired value. The general IMC structure is shown in Figure 1. The distinguish characteristic for IMC is the process model, $\acute{p}$ which is parallel to the process, p giving it a disturbance estimation ability. If the process model $\acute{p}$ is equal to process p, then the estimated disturbance is the actual disturbance d to the system. It is a best practice for the process model to implicitly or explicitly representing the model so that the theoretical prefect control can be achieved. Based on the theory, if the p(s) = $\acute{p}$ (s) and q(s) = $\acute{p}^{-1}$(s), by using the minimum phase of the inverse model $\acute{p}^{-1}$(s) and introduce filter to make the controller physical realizable, the IMC controller, q will has the ability to eliminate any deviation from the setpoint r , hence, achieving the prefect control.

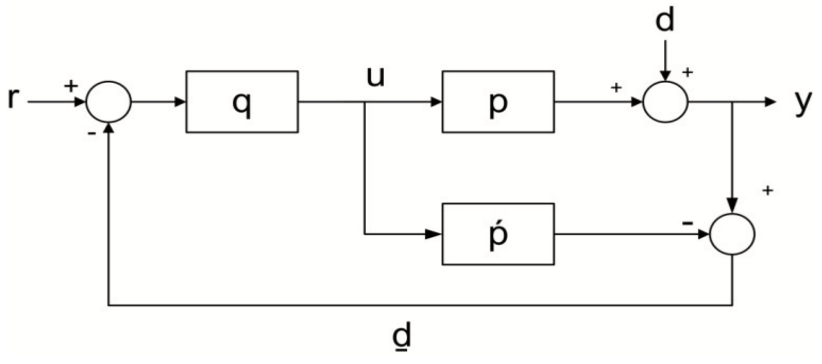

Figure 1: The IMC structure

It is recognized that IMC have the following criteria [Economou *et al*., 1986]:

- Dual Stability: By assuming that p(s) = $\acute{p}$ (s), that is the process model and the process is identical, and if the controller and the process are stable, then the IMC structure can guarantees the closed loop stability.
- Perfect control: By assuming that q(s) = $\acute{p}^{-1}$(s), that is controller is equivalent to the inverse model and the closed loop system is stable, then there is no output steady-state error for set point variance and disturbance.
- Zero Offset: By assuming that the steady state gain controller is equal to the inverse model gain and the closed loop system in Figure 1 is stable, for constant set point and disturbance, there will be no offset.

The Internal Model of IMC is a significant part in IMC design. The robustness and performance of the model is important as the response from the model will be used to adjust the controller action to the system. There are many process models that are available from the First Principle Models (FPM) which utilize the fundamental knowledge of the process in its design, Empirical Models which is the correlation relationship between input-output data and the integration of both FPM and Empirical Models. The types of models that have been applied in continuous distillation column have been reviewed by Abdullah *et al*. [2007].

3. IMC APPLICATION IN CONTINUOUS DISTILLATION

The IMC had been applied in several areas in chemical process such as in CSTR reactor [Varshney *et al*., 2009; Zhang and Li, 2009], batch reactor [Azwar *et al*., 2006; Liu *et al*., 2010], pH control [Jalili-Kharaajoo *et al*., 2003; Wang and Shi, 2005], and distillation [Han and Clough, 2006; Li *et al*., 2009]. However, this paper will review the application of IMC in the continuous distillation column only.

Garcia and Morari [1985] as the pioneer in the IMC, was the first to utilize the IMC in the continuous distillation. They had demonstrated the multivariable IMC design using binary distillation model from Woods and Berry [1973]. The IMC design was based on discrete time transfer function and its performance was compared with the Proportional Integral (PI) control and the multivariable dead-time compensator (ORC). In their work, the optimal factorization matrix was used to make the controller realizable. In the perfect controller response, the IMC system exhibit perfect decoupling and achieve its setpoint in two minutes despite of strong input action. For servo response, SISO PI control alone gave high oscillation and interaction. When ORC is used with PI controllers, a smoother approach to setpoint was achieved yet, the interaction was still strong and the settling time is quite long. For IMC, the result was better from both PI with or without ORC regardless of the interaction. In their study, the design of Feedforward IMC (FFIMC) using feedforward compensator to eliminate the effect of disturbance and the disturbance delay was also discussed.

Wassick and Tummala [1989] had proposed a multivariable modified Feedforward IMC (FFIMC) to control an industrial distillation column. The two input and two output linear model of the industrial distillation column was build based on experimental data using discrete-time transfer function. Due to the high order of the system, the controller had been designed from an inverse of a reduced-order model of the process. This can reduce the high-frequency control actions and complexity of the control program. Besides that, the advantage of FFIMC was the measurable disturbance in the process was compensated by the FFIMC to cancel their effect on the process. The modified part of the FFIMC was to allow the feedback control calculations for both controllers to be made independently, and then their results were processed and added to each other to determine the overall control signal. Since the controller was based on multirate sampling, a critical decoupling was introduced and a trailing average of overhead controller output was used for bottom controller. In their study, the controllers were developed from discrete-time transfer function. From their simulation, the advantage of the modified FFIMC over PI control had been demonstrated.

Basualdo *et al*. [1994] had implemented the Artificial Neural Network (ANN) in the IMC design for the Toluene-Benzene distillation system. The multilayer feedforward neural network was used as the ANN architecture and system identification of this process was developed from simulation data. The reflux stream and its consequent product composition at different operation points were selected as the input to the network. For the ANN training purpose, the Back Propagation (BP) algorithm was used as it is capable to control dynamic process. In their study, a feed forward neural emulator was developed to estimate the distillate composition of the column to represent the internal model of an IMC control structure and the controller was build from neural network model as well. The result of their study for the top composition control of the distillation column showed that Proportional-Derivative (PD) control using ANN Inverse Model has demonstrated a better performance than pure IMC.

Fieg *et al*. [1996] had compared the performance of the IMC with the decentralized discrete time PI controller for the study of the possibility of a direct concentration control for an industrial oleochemical distillation column. The research had been proposed to deal with measurement delay by using online gas chromatography (GC) and problems in using tray temperature control as the oleochemical products temperature is less sensitive. In their approach, the steady state decoupling by output transformation was introduced to the PI control. The IMC was developed based on linear model of Laplace domain transfer function. Based on the simulation study, the IMC gave better results in settling time and less swinging compared to the PI control strategy.

Shaw and Doyle III [1997] had used IMC based on Recurrent Dynamic Neural Network (RDNN) model for a two inputs and two outputs for high purity distillation column. RDNN structure was similar to Recurrent Neural Network (RNN) structure where it incorporates dynamic elements with continuous feedback. The difference is the RDNN weight is based on nonlinear functions of the outputs. This will give the network additional ability to cover a wider range of nonlinear behavior. In their IMC design framework for controller, the Input-Output Linearization (IOL) techniques were chosen because of the control affine nature of the RDNN structure. IOL techniques transform the nonlinear input-output map into linear although the system is nonlinear. However, the use of IOL is limited to modeling of minimum phase systems and system with invertible characteristic matrix. This RDNN control system was tested on the first principle nonlinear model to simulate a two input-two output high purity distillation column. From the study, the integration of a priori information such as two-time constant of the distillation behavior helped to improve the model for open loop simulation. From the closed loop simulation and Singular Value Decomposition (SVD) analysis, a model identified with both open loop and closed loop data gave better control performance than model identified solely with open loop data.

Murad *et al*. [1996 & 1997] had proposed design procedures to incorporate 2 Degree of Freedom (2-DOF) IMC with $H\infty$ optimization framework. The application of $H\infty$ control in the control system was to synthesize controllers in achieving robust performance and stabilization. The IMC controller was generalized by $H\infty$ optimization technique according to the proposed design procedures in discrete time and in state space form. The control system was implemented in an experimental methanol-water distillation column model. The new control strategy has shown great potential in servo behavior and provides fast settling time. The results from the model mismatch test also proved that the control strategy was robust.

Another application of 2-DOF IMC is the Combined Internal model and Inferential Control (CIMIC) by Häggblom [1996]. CIMIC is a control strategy that incorporates IMC design features such as using process model and at the same time, executes inferential control strategy to infer the disturbance from secondary output measurement. CIMIC is a continuity development from Disturbance Rejection and Decoupling (DRD) structure carried out by Haggblom and Waller [1990]. The DRD structure managed to yield perfect decoupling in steady state and the rejection of disturbance in feed flow, F and the feed composition z, even in the condition where the disturbances were not measured and without primary feedback. In their work, the CIMIC design specification was based on linear control system and state space representation. The control system was developed to compare with pure internal model control (IMC) performance in controlling a pilot scale distillation column for a binary system. The performance of CIMIC in the study was not as distinct as expected due to the primary output (tray temperature) respond almost as fast as the secondary output (inventory control variables). Yet, the results show some promising leads of CIMIC application if the nonlinear model was used and the product composition control was considered as the control objective.

Venkateswarlu and Gangiah [1997] had compared the performance of Nonlinear IMC (NIMC) with on-line estimator with globally linearizing control (GLC) and generic model control (GMC) strategies for distillation column startup and operation. The NIMC approach used the nonlinear filter that can be adjusted for process or model mismatch. The new input for the NIMC was derived to obtain the control algorithm and the design was based on continuous linear transfer function. The rigorous dynamic column distillation model from Wood and Berry [1973] was used in the research. The study concluded that the NIMC strategy was recommended due to easy tuning and best transition from total reflux mode to steady-state condition.

Wang *et al*. [2002] had proposed a new approach to the IMC analysis and design for decoupling and stabilizing of multivariable stable processes with multiple time delay. In their study, the characteristic of stable IMC had been formulated in terms of time delays and non-minimum phase zeros for the open-loop system. Based on this characterization, the control design procedure was developed for best performance and further simplified using model reduction technique. The resulting controller was in the form of proper second order transfer functions in a state space form. The study of the effectiveness of the proposed decoupling IMC design and the effects of time delays and non-minimum phase zeros was applied in the binary distillation column from Wood and Berry, [1973]. The results indicated that the performance of the proposed IMC design was significantly better and its response was very close to the response obtained with the ideal decoupling IMC controller.

Jones and Tham [2004] had presented the IMC-PID design and compared it with Gain Phase Margin (GPM) based PID. Both control strategy are applied to a multi-loop PI control configuration which is being used to control a multivariable process in the distillation column from Woods and Berry [1973]. The IMC-PID design method was easier to develop as it has only one design parameter related to desired time constant of the closed loop response. Meanwhile, the GPM-PID had two design parameters that allow a more flexibility in the control design. In this case, the Simplified IMC (SIMC) had been used based on First Order Plus Time Delay (FOPTD) for bottom loop and Integral Plus Time Delay (IPTD) design method in distillate loop control. On the other hand, the GPM-PID design was based only on IPTD design method. The overall test in closed loop and process model mismatch showed that GPM approach performs better than IMC, although choosing the appropriate gain and phase value can be difficult for GPM design.

Chawankul *et al*. [2005] had studied the integrating cost of variability in the controlled variables (control cost) with capital and operating costs (design cost) into one cost objective function by using IMC to demonstrate a single input single output (SISO) system. The FOPDT model was assumed to represent the process and model uncertainty was introduced to study the variability of the process. A robust control approach using IMC was designed with the presence of model uncertainty to account for nonlinearity with respect to the nominal model. The IMC controller was designed based on performance weight to study the variability cost. As a case study, simulation of depropanizer distillation was carried out using Aspen Plus process simulator. Based on this new approach, the performance weight of the control variability was directly associated with price, capital, and operating cost. From the effect of uncertainty study, it was found that the distillation reflux ratio should be selected at a low level since the uncertainty in the time delay, due to nonlinear effects, is relatively small. The proposed integrated method approach results significantly increase the cost savings compare to the traditional method where the design and control steps are performed separately in a sequential fashion.

A combination of Feedback and Feedfoward Control with IMC concept also had been proposed for two-point temperature control in binary distillation column by Castellanos-Sahagun *et al*. [2005]. In their work, the methodology includes the structure, construction, and tuning aspects of the control design problem of the linear two-point temperature was explained. The decentralized one-way and two-way decoupling control structure was also studied. The control model was consisted of linear integrator based on control input, an effective load disturbance and steady state parameters that gather the relevant interaction data. The controller consist of a static interaction compensator with a pair of decoupled feedforward-feedback control loops, with setpoint adjusters for feed temperature, built from the static output temperature correlation on the feed temperature. They found out that the proposed control system was able to capture the behavior similar to a model-based feedforward-feedback material balance controller.

Razzaghi and Shahraki [2007] had studied the application of IMC-PID control for a high purity distillation column model. The column model was developed with the uncertainty and dynamic behavior of the high purity column for the entire operating condition. A Structured Singular Value (SSV) which was defined in terms of the $H\infty$-norm of the weighted sensitivity function was used to synthesize the controller and evaluate the control performance. The decentralized linear IMC based PID model was developed and the good set-point tracking and disturbance rejection of the controller has been observed by simulation results.

Shamsuzzoha and Lee [2008] had proposed a simple analytical design method for PID filter controller based on IMC concepts for First Order Delay Unstable Process (FODUP) model and Delay Integrating Process (DIP) model. The robustness study was conducted by inserting a perturbation uncertainty in all parameters simultaneously to obtain the worst case model mismatch and had compared it with methods proposed by Chen and Seborg [2002] and Lee *et al.* [2000] in designing the PID controller. The results demonstrated that the proposed technique was better than the both in servo and regulatory problems.

The summary of the IMC applications in continuous distillation column that are discussed in this paper are tabulated in Table 1.

Table 1: The IMC Application in Continuous Distillation Column

No.	**Authors**	**Year**	**Type IMC**	**Distillation System**	**Implementation**
1	Garcia and Morari	1985	Linear	Methanol-Water	Simulation
2	Wassick and Tummala	1989	Linear	Styrene - Ethyl benzene	Simulation
3	Basualdo *et al.*	1994	Nonlinear	Benzene-Toluene	Simulation
4	Fieg *et al.*	1996	Linear	Oleochemical components	Simulation
5	Shaw and Doyle III	1996	Linear	Ethanol-Methanol	Simulation
6	Murad *et al.*	1996	Linear	Methanol-Water	Simulation
7	Häggblom	1996	Linear	Ethanol-Water	Experiment
8	Venkateswarlu and Gangiah	1997	Nonlinear	Methanol-Water	Simulation
9	Murad *et. al*	1997	Linear	Methanol-Water	Simulation
10	Wang *et al.*	2002	Linear	Methanol-Water	Simulation
11	Jones and Tham	2004	Linear	Methanol-Water	Simulation
12	Chawankul *et al.*	2005	Linear	Ethane-propane-isobutene-N-butane-N-pentane-N-hexane	Simulation
13	Castellanos-SahaguÌ *et al.*	2005	Linear	Benzene-Toluene and Methanol-Water	Simulation
14	Razzaghi and Shahraki	2007	Linear	n/a	Simulation
15	Shamsuzzoha and Lee	2008	Linear	n/a	Simulation

From the table, most of the researchers had applied linear model whether in discrete or continuous transfer function domain within the IMC. In nonlinear model based IMC, only Neural Networks model had been applied. Moreover, the distillation system considered was focused only to the separation of binary components rather than multi components distillation. It is known that the addition of the components will contribute towards more dynamic behavior which will make the control part become more challenging. Additionally, almost all of the works were conducted in simulation environment. However, some of the researchers incorporate time delay and nonlinearities in their model to simulate the real condition.

4. CONCLUSIONS

The works related to the application of IMC in continuous distillation column system for the last 28 years had been reviewed. From the review, IMC has a potential to be a robust control system and can be successfully implemented in continuous distillation column. However, the application of IMC in this area is still limited to Linear Model based IMC design framework. Furthermore, most of the research works were based on binary distillation simulation. Thus the feasibility of this proposed model based control strategy to be implemented in a more nonlinear dynamic and higher order process such as multi component distillation which is mostly practiced in the industries is still in doubt. Therefore, the study of IMC implementation in real time or in pilot plant for multicomponent distillation is important in order to prove the feasibility of the control strategy. Moreover, there is still limited number of research work focus on Nonlinear Model based IMC in the continuous distillation column.

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