MULTIVARIABLE CONTROL STRATEGY BASED ON BIFURCATION ANALYSIS OF AN INDUSTRIAL GAS-PHASE POLYMERIZATION REACTOR

Nina P. G. Salau[1], Argimiro R. Secchi[2], Jorge O. Trierweiler[3], Gustavo A. Neumann[4]

[1,2,3]Group of Integration, Modelling, Simulation, Control and Optimization of Processes (GIMSCOP)
Department of Chemical Engineering, Universidade Federal do Rio Grande do Sul (UFRGS), Brazil
[4]BRASKEM S. A.- Brazil
{[1]ninas, [2]arge, [3]jorge}@enq.ufrgs.br , [4]gustavo.neumann@braskem.com.br

Abstract: In an industrial gas-phase polyethylene reactor, the safe operating range of temperature is rather narrow. Even within this temperature range, temperature excursions must be avoided because they can result in low catalyst productivity and significant changes in product properties. In previous work, using a first-principles model, including the recycle stream and the heat exchange system, a PID temperature controller with robust performance was designed via optimization in the frequency domain for different operating points. For the reactor total pressure, ethylene partial pressure, H2/C2 and C4/C2 molar ratios, PI controllers were designed. In the PID temperature controller, if the manipulated variable (cooling water valve opening) saturates then the reactor operates without a feedback temperature controller, leading to oscillatory behaviour and limit cycles. It has been demonstrated that the manipulated variable saturation and the nonlinear dynamic behaviour are removed when auxiliary manipulated variables, obtained by bifurcation analysis, are used in a multivariable control strategy for the reactor temperature control. In this work, two control structures are compared to define the most suitable proposal for implementation in an industrial reactor and the impact of these control structures in the reactor production and in the polymer melt index are analyzed. The first control structure considers the control problem using the designed PID controller for the reactor temperature and includes a switching strategy with a PI controller for the auxiliary manipulated variables. The second control structure considers the control problem also using the designed PID controller for the reactor temperature, however including a MPC controller for the auxiliary manipulated variables.

Keywords: Multivariable Control Strategy, Bifurcation Analysis, Polymerization Reactor, and Stability.

1. INTRODUCTION

Stabilization of polyethylene reactors is a challenging problem and needs to be addressed through a good control. Dadebo et al. (1997) have demonstrated that without feedback control, industrial gas-phase polyethylene reactors are prone to unstable steady states, limit cycles and excursions toward unacceptable high temperature steady states. In their work, the ability of the controllers to stabilize desired setpoints of industrial interest is evaluated using a bifurcation approach. Seki et al. (2001) have studied the stabilization of gas-phase polyethylene reactors through an adequate tuning of PID controller, which is applicable regardless of the pole locations of the transfer function and have been proposed a retuning method of a PID controller, which can be performed at the onset of closed-loop instability.

In their paper, Ali et al. (2003) have investigated a multivariable control problem of an industrial gas-phase polyethylene reactor, where are considered the two time-scale of the process and the multi-rate sampling of the process variable control. Specially, the control of the reactor temperature and pressure in addition to the gas partial pressures is considered in their paper. Two control scheme and two algorithms are tested and compared.

All of aforementioned studies dealt only with the tight regulation of the bed temperature to ensure reactor stability in an operating condition where the saturation does not occur. In this work, a more comprehensive model is used to reproduce the process of an industrial gas-phase polyethylene reactor. In this model, the manipulated variable of bed temperature reactor controller is the control valve opening (the real situation in the industrial reactor), instead of the cooling water temperature. Thus, the saturation of this valve can be accounted for. Besides, in the practical point of view, if the control valve saturates, then the reactor operates without a feedback temperature controller, leading to oscillatory behaviour and limit cycles. Therefore, the manipulated variable saturation and the nonlinear dynamic behaviours should be removed from the system by using auxiliary manipulated variables. In this work, these variables are determined by bifurcation analysis, and then two multivariable control structures for the reactor temperature control are tested and compared to define the best proposal for implementation in industrial reactors.

2. PROCESS MODEL

A fluidized-bed zone and a disengagement zone compose the reactor, as shown in Figure 1. A heat exchanger is used to remove the reaction heat from the compressed recycle stream, and then the cooled gas is mixed with the feed stream to be re-injected in the base of the reactor. The solid catalyst (chromium based) is fed in a stream of nitrogen and then dragged to the fluidized-bed. The product is removed from the reactor by a discharge system operating in cycles determined by the production rate. In the disengagement zone the gas composition is analyzed by chromatography.

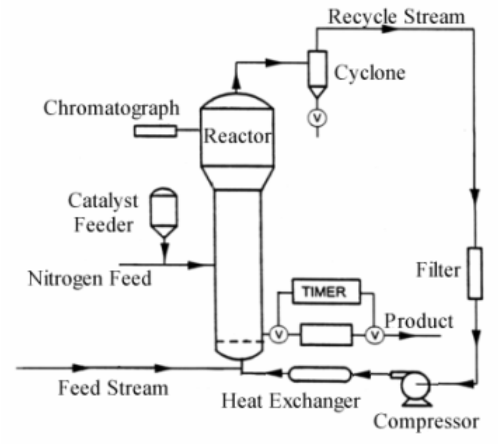

Fig. 1. UNIPOL® process.

The UNIPOL® process model is shown in Figure 2. McAuley et al. (1995) have demonstrated that the additions of the recycle stream and the external cooler models to the reactor model make possible the study of complex dynamics and location of bifurcation points, which could not be reproduced just by the reactor model. Besides, the addition of the heat exchange system, including all their equipments, makes possible an optimal design for the reactor temperature controller, using the cooling water valve opening as manipulated variable. The equations of the model used in this work are detailed in Salau et al. (2005).

3. DYNAMIC BEHAVIOUR ANALYSIS

The effects of the reactor operating conditions on the process dynamics and stability were analysed using the reactor model, including the recycle stream and the external cooler. The developed model was implemented in AUTO®, software for continuation and bifurcation problems in ordinary differential equations. Unstable steady states, limit cycles, and excursions toward unacceptably high-temperature steady states arise during the model simulation, when supposing the reactor operation with open-loop temperature control and the addition of a reactor total pressure controller to the system, whose manipulated variable is the ethylene feed flow rate. These non-linear dynamic behaviours, as shown in Figure 3, can be explained by positive feedback between the reactor temperature and the reaction rate.

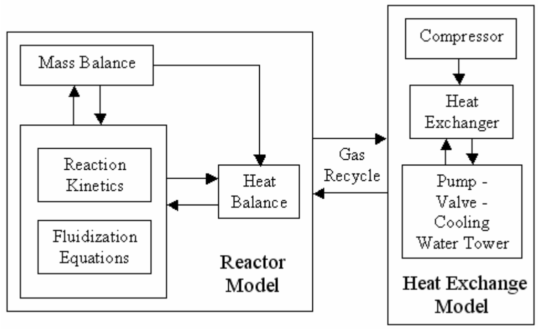

Fig. 2. UNIPOL® process model.

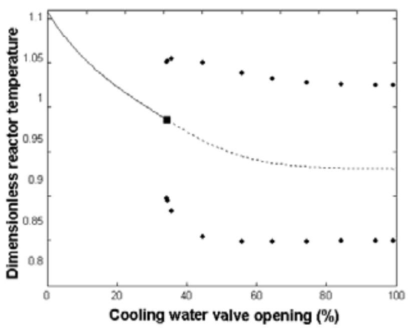

Fig. 3. The effect of cooling water valve opening on stability: — stable steady state; --- unstable steady state; ■ Hopf bifurcation; • stable limit cycles.

If the reactor temperature is above the unstable steady-state temperature, then the heat removal in the heat exchanger is larger than the steady-state heat-generation rate (McAuley et al., 1995). As result, the reactor temperature begins to decrease, decreasing the rate of reaction and the product outflow rate, thereby reducing the rate at which catalyst flows from the reactor. Thus, catalyst and monomer begin to accumulate in the reactor, increasing the temperature, the rate of reaction, and the product outflow rate, resuming the limit cycle.

4. PROPOSED SOLUTION FOR THE REGULATORY TEMPERATURE CONTROL PROBLEM

The reactor system is easily stabilized with a proportional controller. However, the addition of integral and derivative action eliminates offset and leads to faster controller performance (Dadebo et al., 1997). The advantages of a PID controller in this case are the speed and thereby the sample time, the rejecting disturbances, the robustness and the trustworthiness.

Due to high non-linearity between the reactor temperature and cooling water valve opening, the relation between these variables were characterized by a multi-model system (many representative linear models of different operating region). The linear models used to design a robust PID controller were built at the points that belong to the unstable regions of valve opening, shown in Figure 3. Thus, the PID temperature controller was designed using the SIOM-MMA (Sequential Iterative Optimization Method - Multi-Model Approach, Faccin and Trierweiler, 2004), based on a frequency domain optimization problem for a given desired performance. The method is able to design a PID controller for different operating points with robust performance, as shown in Figure 4.

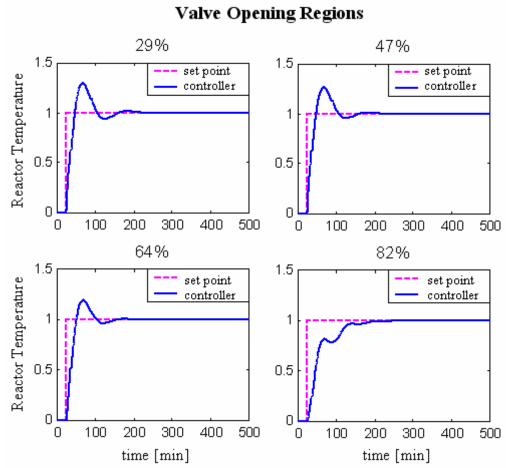

Fig. 4. Temperature response for a step setpoint change using the robust PID controller.

For better representation of industrial plant operation conditions, PI controllers were designed to reactor total pressure, ethylene partial pressure, H2/C2 and C4/C2 molar ratios, whose manipulated variables are, respectively, ethylene, nitrogen, hydrogen and butene feed flow rate. A MPC temperature controller also was designed in order to obtain a similar performance of the PID temperature controller. Thus, some tests were carried out, using the linear and the non-linear model, to demonstrate the controllers' performance in regions where the valve operates in a nominal condition and where the valve moves in the fully open direction, in other words, operates in a saturation condition. The controllers' performances for a step setpoint change and a step disturbance in the reactor temperature using the linear model (of a nominal operating condition of valve opening) is shown in the Figure 5 and using the non-linear model is shown in Figure 6. According to Figure 5, the MPC temperature controller presents a better performance for a step setpoint change and a worst performance for an unmeasured disturbance rejection (presenting an oscillatory behaviour) than the PID temperature controller. However, in the industrial plant there are many unmeasured disturbances, which cannot be modelled and, according to Figure 6, the MPC temperature controller fails for a step setpoint change when subject to unmodelled disturbances, causing oscillatory behaviour and leading the reactor operation to a limit cycle. On the other hand, satisfactory results were obtained for a step setpoint change and for unmeasured disturbance rejection using the non-linear model in a nominal operating condition with the designed PID temperature controller.

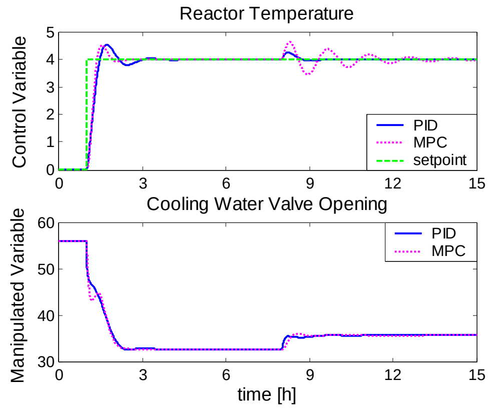

Fig. 5. Reactor temperature and valve opening cooling water responses for a step setpoint change at time of 1 hour and for a step disturbance at time of 8 hours with the PID and the MPC controller using the linear model.

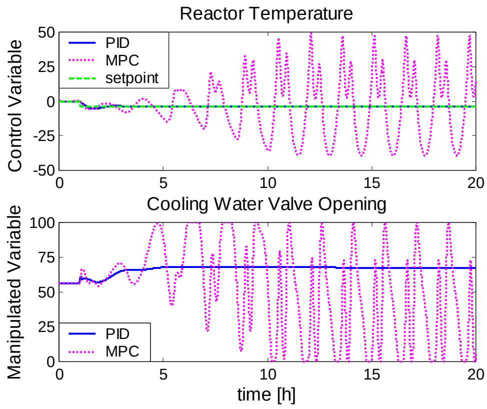

Fig. 6. Reactor temperature and valve opening cooling water responses for a step setpoint change at time of 1 hour with the PID and the MPC controller using the non-linear model.

It is shown in Figure 4 that as the valve moves in the fully open direction, the controller performance degrades. A better controller performance could be achieved using a gain-scheduling strategy. However, according to Figure 3, the gain in the reactor temperature as the valve moves after an opening of 80% in the fully open direction is practically ineffective because, in these conditions, the heat exchange does not occur due to the system thermal limitation. Besides, if the control valve saturates (a common situation in the industrial reactor), then the reactor operates without a feedback temperature controller, leading to oscillatory behaviour and limit cycles, as shown in Figure 7. Thus, the use of gain-scheduling strategy was ruled out. Therefore, manipulation of valve opening alone may not be sufficient to bring the temperature back to the desired level. Thus, auxiliary manipulated variables need to be determined in order to move the reactor away from region where the limit cycles occur.

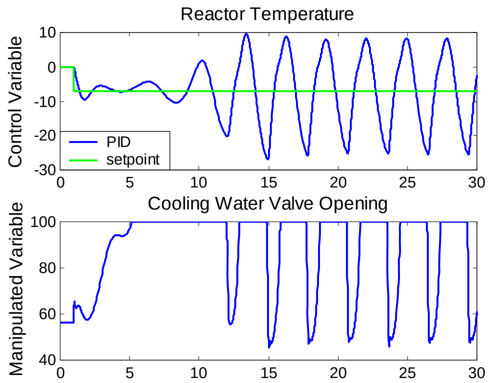

Fig. 7. Reactor temperature and valve opening cooling water responses for a step setpoint change at time of 1 hour with the PID controller using the non-linear model in a saturation operating condition.

5. FEASIBLE OPERATING REGIONS

Candidate auxiliary manipulated variables, that can be manipulated to reduce the reactor temperature, are catalyst feed rate, inert saturated organic feed rate, and ethylene partial-pressure controller setpoint. All these variables can stabilize the reactor temperature controller in the desired setpoint by reducing the rate of heat generation or increasing the heat transfer capacity (Salau, 2004). However, all of these variables reduce the production rate and other problems may arise with their use, some of them are shown in Table 1.

Table 1. Problems in using auxiliary manipulated variables to help control the reactor temperature.

Variables	Problems
Catalyst feed rate	It is difficult to determinate the flow rate in the feeder due to its small sensibility. High impact in the reactor production.
Inert saturated organic feed rate (low boiling point)	If the gas mixture dew point is achieved, the distributed plate of gas in the reactor will block. To prevent accumulation, the inert has to be removed from the reactor through the product or purge streams.
Ethylene partial-pressure controller setpoint	It causes a decrease in the recycle heat exchange capacity, by increasing the nitrogen/ethylene concentration ratio.

In the industrial unit, due to the high correlation between the reactor total pressure and the ethylene partial pressure, the operator manually controls the last one through the nitrogen feed rate or the bleed stream. As the reactor total pressure is controlled through the ethylene flow rate manipulation, to use the ethylene partial-pressure controller setpoint in the multivariable control strategy would be necessary to design a controller strategy for the reactor using the total pressure and the ethylene partial pressure, simultaneously. Thus, only the catalyst and the inert saturated organic feed rate were used in this work.

To prove the potentiality in using auxiliary manipulated variables to help control the reactor temperature, it was made a bifurcation study in open loop where the evaluated state variable is the reactor temperature and the bifurcation parameters are: valve opening cooling water (the manipulated variable of the PID temperature controller), and catalyst feed rate and inert saturated organic feed rate (the auxiliary manipulated variables to be used in the reactor temperature control). In Figure 8 is shown the effect of two different values of inert saturated organic feed rate on stability with valve opening cooling water and catalyst feed rate as bifurcation parameters. In Figure 9 is shown the effect of two different values of catalyst feed rate on stability with valve opening cooling water and inert saturated organic feed rate as bifurcation parameters.

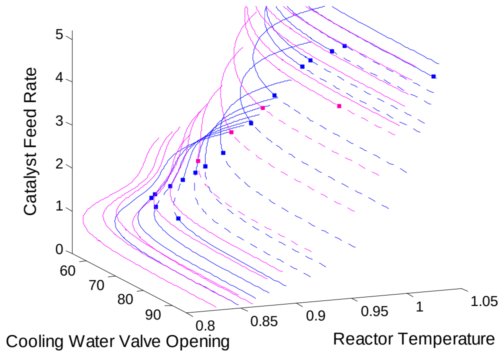

Fig. 8. The effect of a lower (in blue) and a higher (in magenta) inert saturated organic feed rate on stability: — stable steady state; --- unstable steady state; ■ Hopf bifurcation.

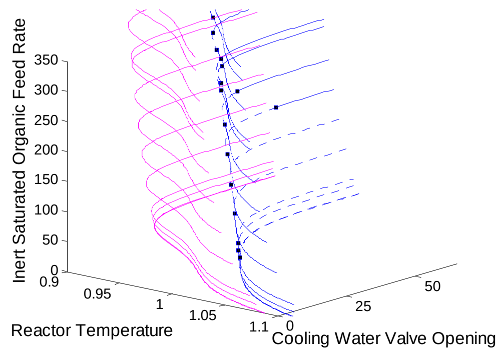

Fig. 9. The effect of a higher (in blue) and a lower (in magenta) catalyst feed rate on stability: — stable steady state; --- unstable steady state; ■ Hopf bifurcation.

According to Figure 8, if the inert saturated organic feed rate is increased, the region of stability for different catalyst feed rates increases, reducing the reactor temperature and the valve opening cooling water. In Figure 9, it is shown that if the catalyst feed rate is reduced, the region of stability for different inert saturated organic feed rates also increases, reducing the reactor temperature and the valve opening cooling water. As a small reduction in the catalyst feed rate has a negative large impact in the reactor production, and the increase in the inert saturated organic feed rate enlarge the stability region keeping the catalyst feed rate at the nominal operating point, the best strategy is the use of inert as auxiliary manipulated variable as much as possible.

6. PROPOSED SOLUTION FOR THE SUPERVISORY CONTROL PROBLEM

In the supervisory control problem, the reactor temperature PID controller, designed using the SIOM-MMA method, was maintained and the valve opening, which is the manipulated variable of this controller, becomes the controlled variable in two different control structures within a multivariable strategy: a sequential PI switch controller and a model predictive controller (MPC). The idea of these control structures is open the control valve through the reactor temperature PID controller, until achieving a region where the gain between the valve opening and the cooling water becomes low. When a pre-determinate value of the valve opening is achieved, the inert saturated organic feed rate, with high specific heat capacity, is increased to improve the heat exchange between the recycle gas and the cooling water. Thereby, more reaction heat is removed from the reactor, decreasing the reactor temperature back to the setpoint. However, the maximum amount of this inert saturated organic feed rate is limited by the gas mixture dew point. When this upper bound is achieved without stabilizing the reactor temperature in the setpoint, the catalyst feed rate is reduced to decrease the reactor temperature.

The first control structure considers the control problem using the designed PID controller for the reactor temperature and includes a switching strategy with a sequential PI controller for the auxiliary manipulated variables. The second control structure considers the control problem also using the designed PID controller for the reactor temperature, however, including a MPC controller for the auxiliary manipulated variables. The responses of both sequential PI switch controller and MPC are compared to define the most suitable proposal for implementation in an industrial reactor.

6.1 Results for a Nominal Operating Condition

It was chosen a nominal operating condition to compare the control problem using only the reactor temperature PID controller (Figure 6) and the control problem using the two proposed multivariable control structures (Figures 10 and 11). In the multivariable control structures, the inert saturated organic feed rate is increased after the valve opening achieves 60%, and the catalyst feed rate is decreased after the inert saturated organic feed rate increases 3 dimensionless units. According to Figures 10 and 11, the performances of both proposed control structures to stabilize the reactor temperature in the desired setpoint are similar. Thus, both controllers are able to get quickly the new polymer melt index, avoiding off-specification product. However, the MPC controller presents a better result than the sequential PI switch controller for a nominal operating condition, because this controller is able to achieve the maximum quantity of the inert saturated organic feed rate before to manipulate the catalyst feed rate and, thereby, reducing production loss.

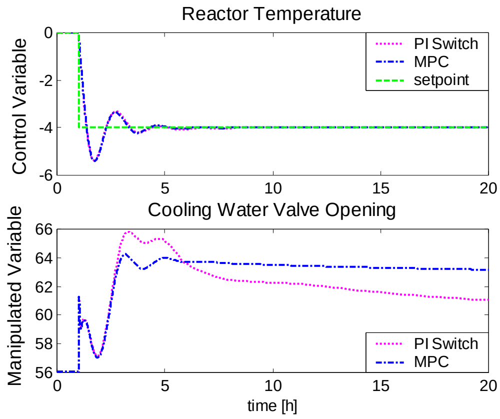

Fig. 10. Reactor temperature and valve opening cooling water response to a step change in reactor temperature setpoint with the multivariable strategy (sequential PI switch and MPC).

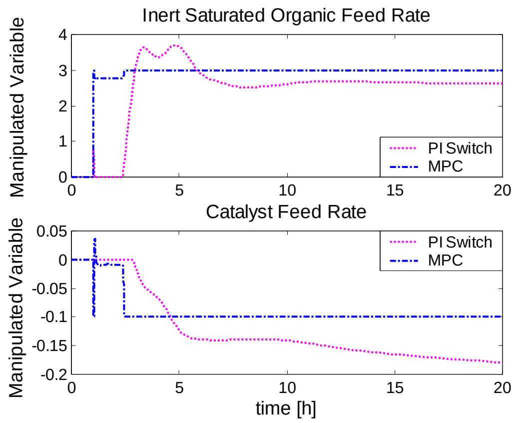

Fig. 11. Inert saturated organic feed rate and catalyst feed rate manipulation with the multivariable strategy (sequential PI switch and MPC).

6.2 Results for a Saturation Condition

It was chosen a valve opening saturation condition to compare the control problem using only the reactor temperature PID controller (Figure 7) and the control problem using the two proposed multivariable control structures (Figures 12 and 13). In the multivariable control structures, the inert saturated organic feed rate is increased after the valve opening achieves 75%, and the catalyst feed rate is decreased after the inert saturated organic feed rate increases 6 dimensionless units. In a valve opening saturation condition, the results for the proposed strategies are similar to the results obtained in a nominal operating condition. Without the multivariable strategies the oscillatory behaviour leads to a limit cycle (Figure 7). In this condition, the MPC controller also is able to achieve the maximum amount of inert saturated organic feed rate before manipulating the catalyst feed rate. Therefore, the MPC controller is more sensitive to the oscillations in the valve opening than the sequential PI switch controller, because the reactor temperature PID controller is operating in a region where the PID performance is poor, according to Figure 4. In this case, a better MPC controller performance can be achieved using a gain-scheduling strategy in the PID temperature controller. The responses of both sequential PI switch controller and MPC with and without a gain-scheduling strategy in the PID temperature controller are compared in Figure 14.

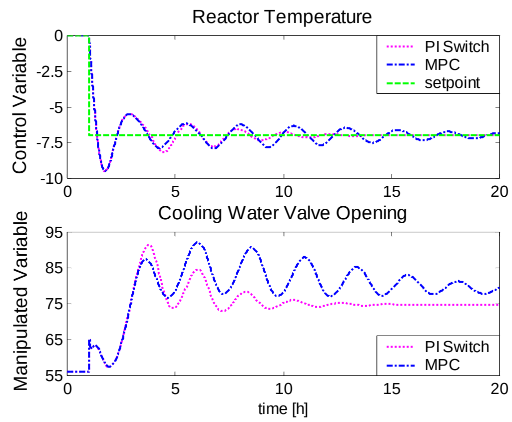

Fig. 12. Reactor temperature and valve opening cooling water response to a step change in reactor temperature setpoint with the multivariable strategy (sequential PI switch and MPC).

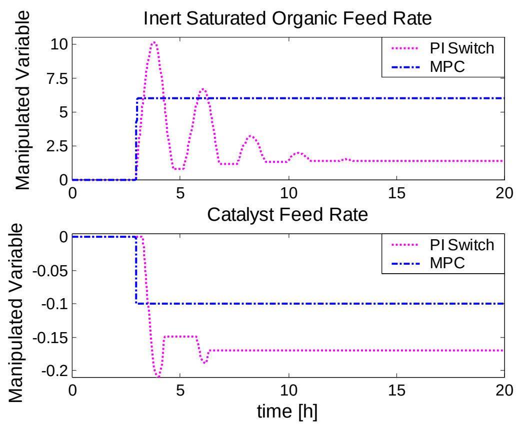

Fig. 13. Inert saturated organic feed rate and catalyst feed rate manipulation with the multivariable strategy (sequential PI switch and MPC).

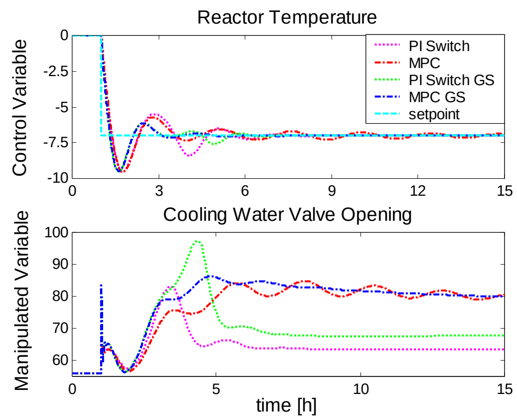

Fig. 14. Reactor temperature and valve opening cooling water response to a step change in reactor temperature setpoint with the multivariable strategy (sequential PI switch and MPC, with and without gain-scheduling).

7. CONCLUSION

It was shown that control of gas-phase polymerization reactors is a difficult task due to high non-linearity of the system and the strong interaction of the process variables. For this challenging control problem, a PID temperature controller with robust performance was designed via optimization in the frequency domain for different operating points. However, when the manipulation of valve opening alone is not sufficient to bring the temperature back to the desired level and this equipment saturates, limit cycles arises in the system. Thus, the use of auxiliary manipulated variables, determined by bifurcation analysis, can stabilize the reactor temperature controller in the desired setpoint by reducing the rate of heat generation or increasing the heat transfer capacity. However, if not properly used, these variables may reduce the production rate and other problems may arise with their manipulation and, consequently, limiting the use of these variables in a multivariable control strategy. The results of this work suggest that the use of gain-scheduling strategy in the PID temperature controller including a MPC controller for the auxiliary manipulated variables for closing the reactor temperature control loop avoids the saturation of manipulated variable and, hence, the undesired non-linear dynamic behaviour. Besides, this controller reduces the production loss and improves the product quality because of its ability to stabilize the reactor temperature in the setpoint with good performance. In order to obtain a better performance of the MPC controller in regions where the control valve moves in the fully open direction, a gain-scheduling in the reactor temperature PID controller, based on the SIOM-MMA approach, showed to be a good choice.

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