

MODEL PREDICTIVE CONTROL OF INTEGRATED UNIT OPERATIONS CONTROL OF A DIVIDED WALL COLUMN

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ABSTRACT

The integration of several unit operations into one common apparatus (process intensification) has the potential to substantially improve the economics of chemical processes if applied to adequate problems. On the other hand, the integration typically causes strong interactions of different process quantities and a loss in degrees of freedom. This may require a more elaborate automatic control scheme. In this study, the control of a divided wall column has been investigated in comparison to the control with a single loop PI controller concept. Although the PI controller concept can be implemented successfully, the model predictive controller shows a considerably improved control behaviour in respect to maximum deviations of the controlled variables and the time to reach steady state.

INTRODUCTION

It has long been known, that the separation of a ternary mixture in three pure fraction can be performed in only one distillation with a vertical „dividing“ wall introduced in the middle section of the column [1]. This configuration has the potential to save about 30% in operation costs and investment respectively. However, it took quite a long time until this technology has been taken in industrial use. So far, about 40 divided wall columns (DWCs) are in operation worldwide, about 30 of them within the BASF group. One reason for this has been the fear to run into controllability problems. Nowadays it could be shown, that divided wall columns can successfully be operated using conventional control strategies implemented with classical PI controllers [2]. However, due to a rather pure control behaviour of these classical strategies, some of the expected savings in energy have to be neglected to run the process at a more stable operation point and some of the expected savings in investment can not be realized due to increased safety margins. This problem should be overcome by the implementation of a more elaborate automatic control scheme like a model predictive controller [3,4].

DIVIDED WALL COLUMNS

Divided wall columns for the separation of a three component mixture compete with the classical separation sequence based on a two column configuration. Numerous publications deal with the choice of the optimum configuration, e.g. [5]. As a rule of thumb, divided wall columns are most economically, if the feed contains about 70 wt-% of the middle boiling component (B) and 15 wt-% heavy boiler (C) and light boiler (A) respectively. In fig. 1, a three component separation of the mixture A/B/C in a two column configuration (direct sequence) is shown in comparison to a divided wall column.

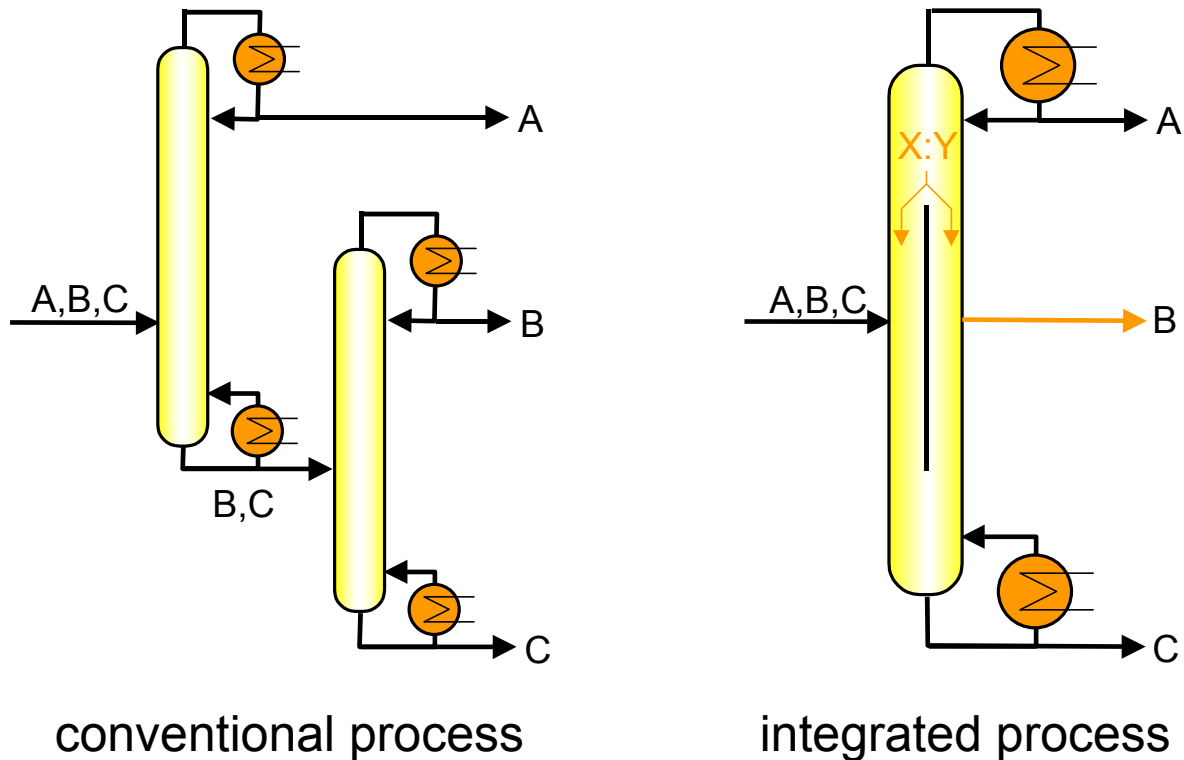


Fig.1: Separation of a ternary mixture in a two column sequence and in a divided wall column

The number of manipulated variables for the two column configuration (left side, fig.1) is 4, that is the heat duty for the reboiler and the reflux ratio for both columns.

For the divided wall column there is only one reboiler and one condenser. An additional degree of freedom is the split range of the internal reflux to the two sides of the dividing wall. The fourth manipulated variable is the amount of side draw (middle boiling component B). As in the conventional process the DWC has four degrees of freedom. However, in most applications the liquid split ratio is fixed by the construction of the liquid distributor above the divided wall section. For technical applications the vapour split ratio below the divided wall is always self-adjusting to give an equal pressure drop over the two parallel branches of the DWC. Hence, in total the DWC has 4 respectively 3 degrees of freedom, an equal number or one less than in the conventional process. Furthermore, there will be strong multidimensional interactions between manipulated and controlled variables. To illustrate this, one can consider the reboiler duty which will effect the product quality of all three products in the DWC, whereas in the conventional process, a change of the reboiler duty of the second column will not effect the product quality of product A.

Although there are conventional control strategies which work well for divided wall columns, this is only valid at operation points with a rather high energy input, thus with a certain distance to the optimum operation point, or if no big disturbances must be considered.

EXPERIMENTAL SET UP

The column used for the studies was mounted in a 3 story cabinet in a miniplant lab at the Ludwigshafen site of the BASF AG. The column section representing the divided wall part was realized by two independent columns in parallel, thus having better access to internal flows and other process information. The total height of the divided wall column was 11.5 m with a column diameter of 40mm for the two parallel columns and 55mm for the upper and lower column respectively. The column was equipped with a falling film evaporator. The complete column was insulated with an active heat compensation to achieve adiabatic operation.

For the investigations, a ternary mixture of butanol (15 wt-%, light boiler), pentanol (70 wt-%, middle boiler), hexanol (15 wt-%, heavy boiler) has been used. The feed ranged from 2 to 3 kg/h. The middle boiler B was taken off as a liquid side draw. The column was operated at 900 mbar.

The column was controlled with an ABB Freelance process control system. The model predictive controller (3dMPC from ABB) was tied in using an OPC interface.

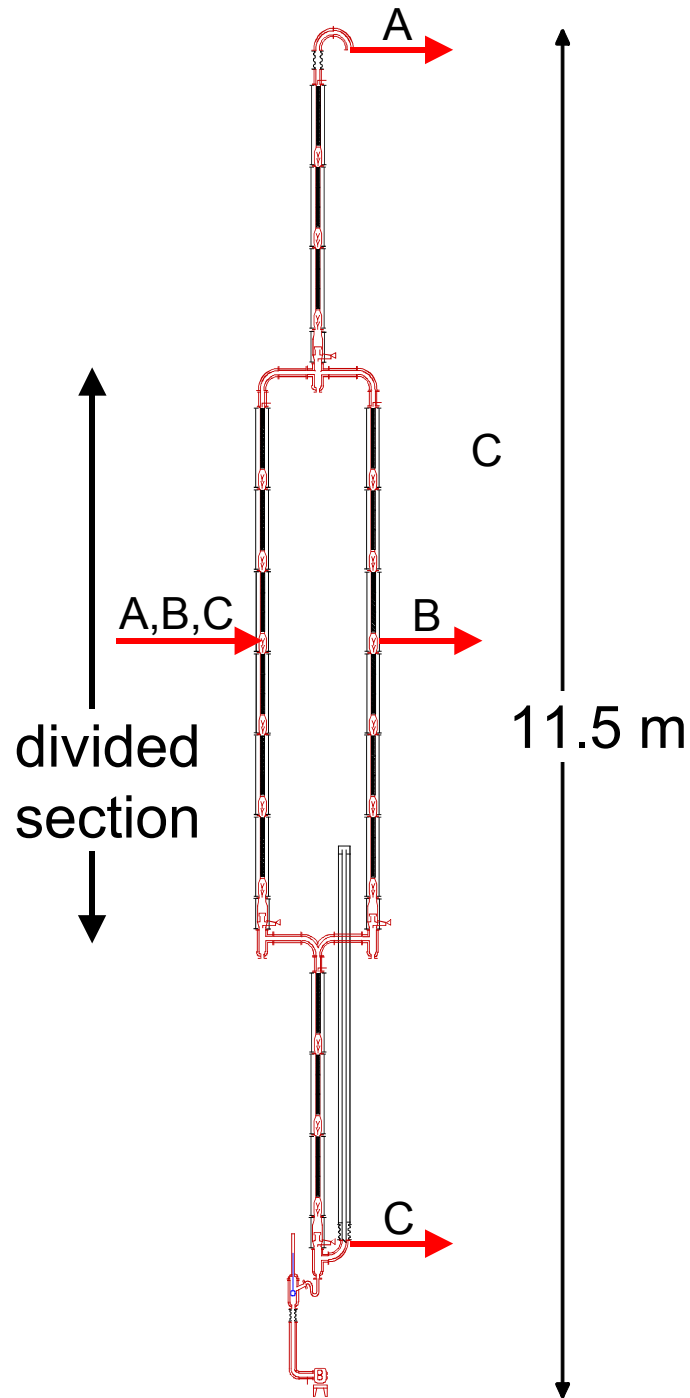


Fig.2: Experimental set up of the divided wall column

CONTROL STRATEGIES FOR DIVIDED WALL COLUMNS

The evaluation of the model predictive control strategy is based on a comparison to a classical control strategy using PI controllers. Different types of PI controller concepts were tested of which the most successful for the case under investigation is shown in figure 3.

PC: pre column
 MC: main column
 UC: upper column
 LC: lower column

<u>Controlled variable</u>	<u>Manipulated variable</u>
temp. precolumn	⇒ reflux ratio
temp. main column	⇒ liquid split ratio
temp. lower column	⇒ amount side draw

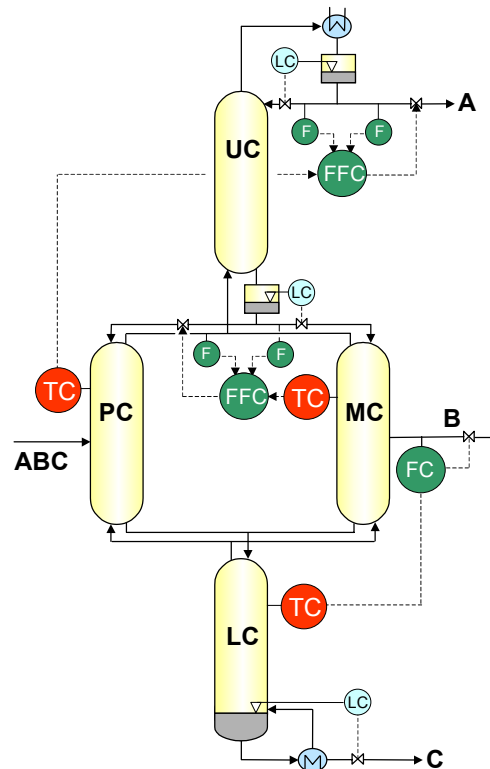


Fig.3: PI controller concept for a divided wall column

As controlled variables, three temperatures in different parts of the divided wall column were chosen.

The temperature in the precolumn (PC) above the feed prevents the heavy boiling component C from passing the upper edge of the dividing wall. Component C passing the upper edge of the dividing wall would partially end up in the product stream B. The temperature is controlled by manipulating the reflux ratio of the upper column.

The temperature in the main column (MC) above the side draw is used to monitor the proper separation of A and B. The corresponding manipulated variable is the liquid split ratio above the dividing wall.

The temperature in the lower column (LC) indicates the inventory of component B. It is controlled by manipulating the liquid side draw. Controlling the temperature in the lower column assures, that no light boiling component A passes the lower edge of the dividing wall as well as no middle boiler ends up in the bottom stream.

Fig. 3 shows that the controlled variables are assigned to specific manipulated variables. This is different with the model predictive controller, where the effects of all manipulated variables to all controlled variables are regarded simultaneously. This makes it possible to handle more manipulated variables than controlled variables. Thus, in the experiments with the MP controller, the heat duty of the reboiler could be used for control purposes additionally resulting in 3 controlled and 4 manipulated variables. It should be mentioned that the control behaviour of the process shown in fig. 3 could be improved to better handle step changes in the amount of feed by implementing a disturbance feed forward control of the reboiler heat duty. However, this would not help for step changes in the feed concentration or set point changes of a controlled variable.

The basic functionality of a model predictive controller is shown in fig. 4 for a one

dimensional control problem (one controlled and manipulated variable respectively). As an example, the response of an MP-controller to a step change in the setpoint of the controlled variable, for example the response of a temperature in a column temperature profile controlled by the reflux as manipulated variable, is considered.

Based on the information of the current process status the future behaviour of the controlled variable is predicted for the prediction horizon using a process model. Generally, there will be a deviation between the value of the controlled variable and the setpoint. This deviation is quantified by the area shown in grey. The model predictive controller tries to minimize this deviation by optimising the time function of the manipulated variable incorporating a dynamic optimisation procedure. Thus, the manipulated variable used to predict the deviation of the controlled variable will change during the control horizon. However, only the first value of the optimised time function for the manipulated variable u_k will be transferred to the process control system. In the next time step, the whole procedure will start again.

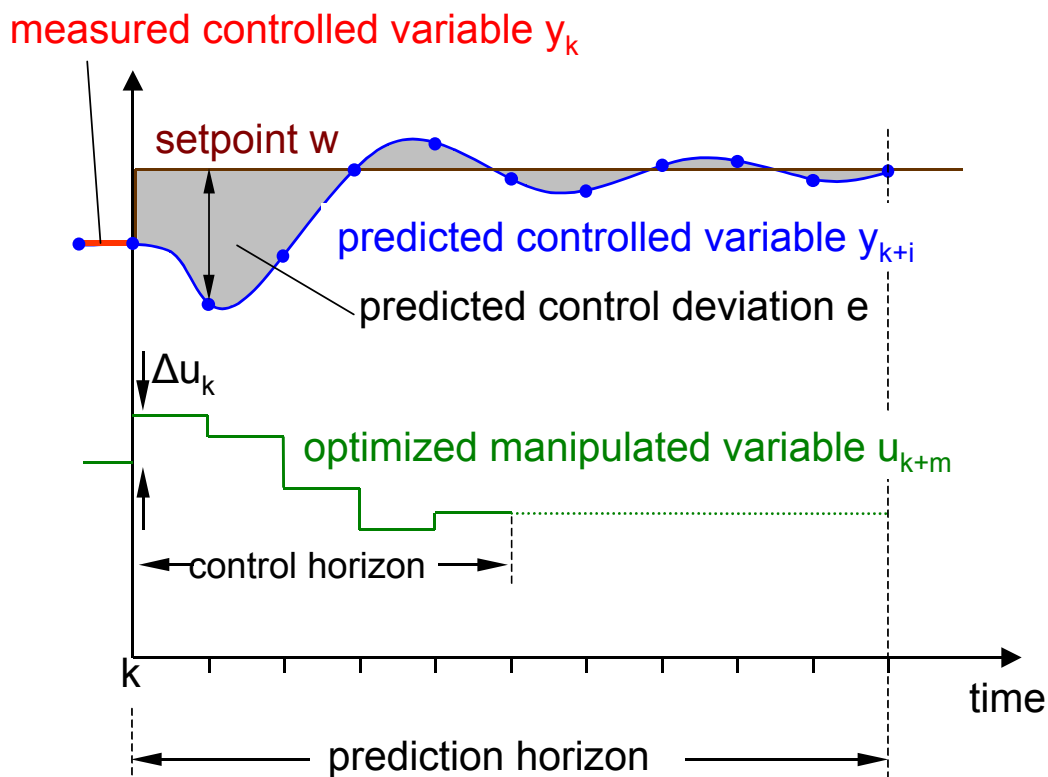


Fig.4: Basic features of a model predictive controller (MPC)

The process model mentioned above is generated by performing identification experiments with the process to be controlled. One set of these identification experiments is shown in fig. 5.

The model identification starts from a steady state run of the divided wall column. While deactivating the column control system, all manipulated variables are changed in a stochastic sequence and direction. This is shown on the left hand side of fig. 5. The manipulated variables used for control purposes were: the reflux ratio, the liquid split ratio, the amount of side draw and the heat duty of the reboiler. In addition, the amount of feed was used as disturbance variable.

As raw data, the resulting time functions of the temperatures, which should be used as controlled variables are registered. Based on these data, a dynamic model of the

divided wall column is generated using the software provided by the supplier of the model predictive controller (ABB).

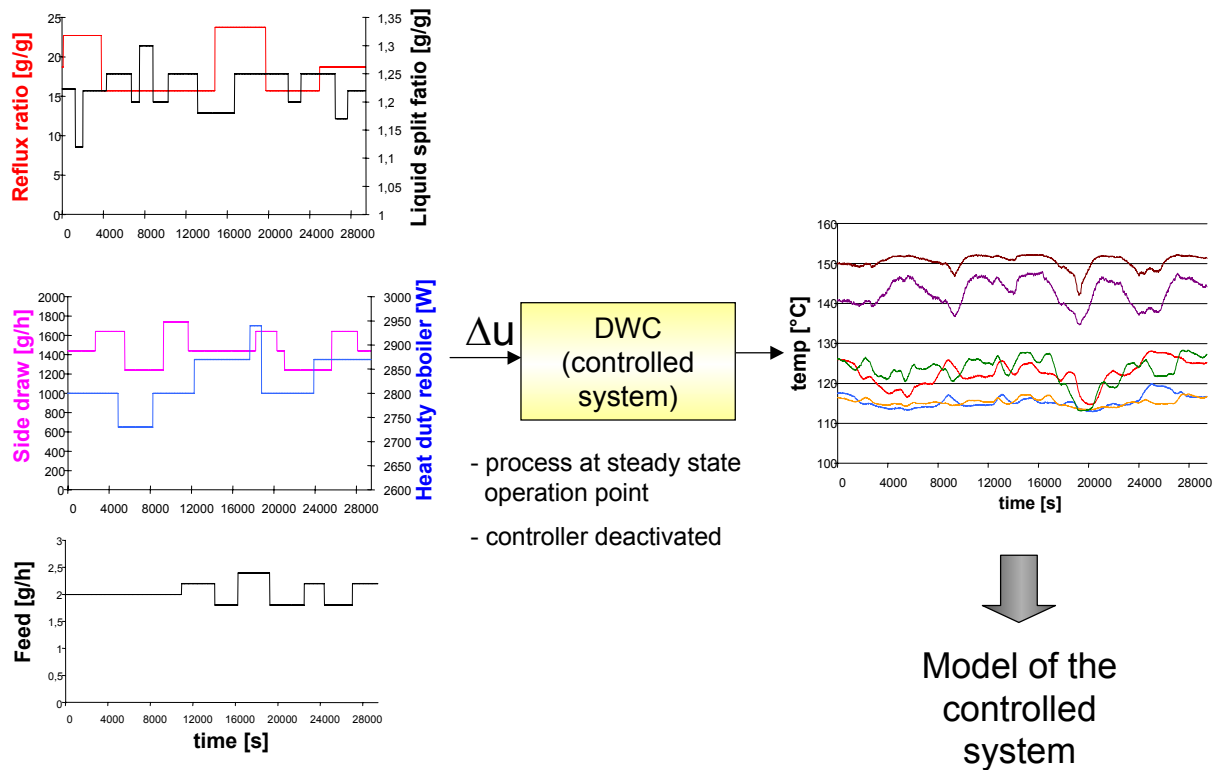


Fig.5: Model Identification for a Model Predictive Controller (MPC)

RESULTS OF THE EXPERIMENTAL CONTROL INVESTIGATIONS

In this section, two sets out of a larger number of experiments will be discussed in detail. The first is the control behaviour of the PI controller concept vs. MP controller concept for a step change in the column feed flow. The second is for a step change in feed concentration. In addition, numerous comparative experiments with step changes to setpoints of controlled variables were performed, which gave the same qualitative results than the two examples and will therefore not be discussed here.

Fig. 6 shows the results for a step change of the feed flow rate to the divided wall. Initially, the column feed was 2.5 kg/h which has been reduced to 2 kg/h. The feed contained 70 wt-% of the middle boiler (pentanol) and 15 wt-% of the light boiler (butanol) and the heavy boiler (hexanol) respectively.

The upper diagram shows the three time functions of the controlled variables, that is the temperatures in the precolumn (red) and the main column (blue) as well as in the lower column (black). For the three controlled variables, the setpoints are indicated by horizontal lines. The next diagrams show the time functions of the manipulated variables, that is the amount of side draw (pink) and the heat duty of the reboiler (blue). In case of the PI controller, the heat duty was not a manipulated variable and therefore not changed. The lower diagram shows the reflux ratio at the top of the upper column (red) and the liquid split ratio to the divided section (black).

The step change of the feed causes an oscillation of the process that has not been vanished even after 12 hours. Reducing the feed rate at constant heat duty of the

reboiler causes the heavy boiler to move upwards in the lower column, leading to a rapid increase in the temperature. To compensate this temperature increase, the amount of side draw is reduced drastically. This however leads to an oscillation of the reflux and liquid split ratio. The maximum deviation of the controlled temperatures lie in the range of 6 to 8 K. It should be mentioned, that a slight improvement of the control behaviour can be expected, if a disturbance feed forward control would be implemented.

Fig. 7 shows the same experiment for the MP-controller. In this case, the maximum deviations of the controlled temperatures lie in the range of 2 to 3 K. Moreover, the time to reach steady state is drastically reduced compared to the PI-controller. It is in the range of 2 hours at maximum. The much improved control behaviour is not only the result of the additional manipulated variable (the heat duty of the reboiler) but also due to the fact, that all manipulated variables react immediately after detecting the disturbance. This can be seen e.g. from the immediate and strong reaction of the liquid side draw.

The results for a step change of the feed concentration are summarized in fig. 8 and fig. 9. In this example, the concentration of the middle boiling component (pentanol) was changed from 70 to 75 wt-%, reducing the light and heavy boiler content by 3.2 and 1.8 wt-% respectively. As could be expected the increased middle boiler content causes an increase of the temperature in the precolumn above the feed, as well as a decrease of the temperature in the lower column. To compensate the higher middle boiler feed rate, the amount of side draw is increased. However, the process reaches steady state only after more than 10 hours and the maximum deviation in the controlled temperatures range from 4 to 6 K when using the PI controller concept.

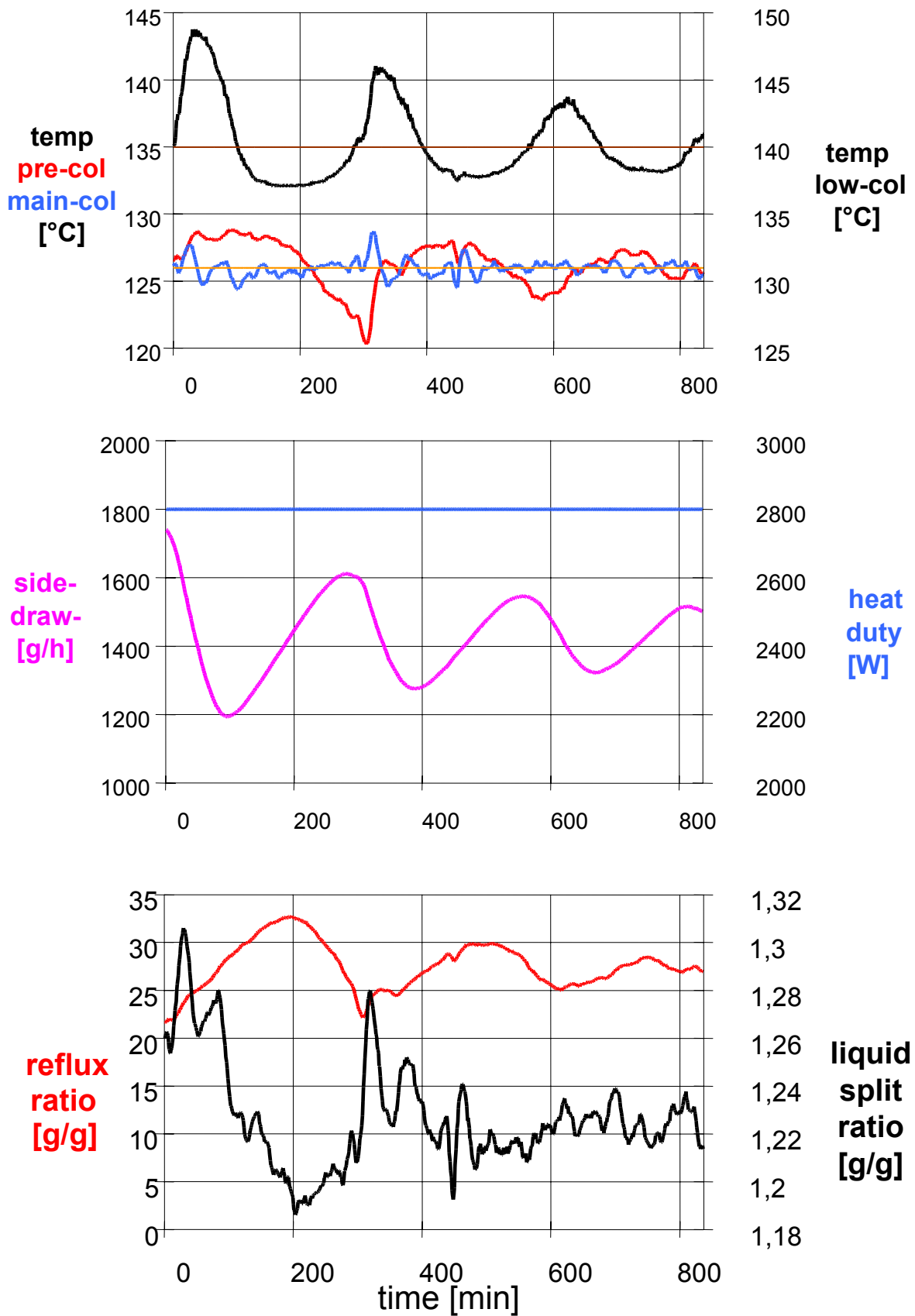


Fig.6: System behaviour for a step change in feed flow: PI controller

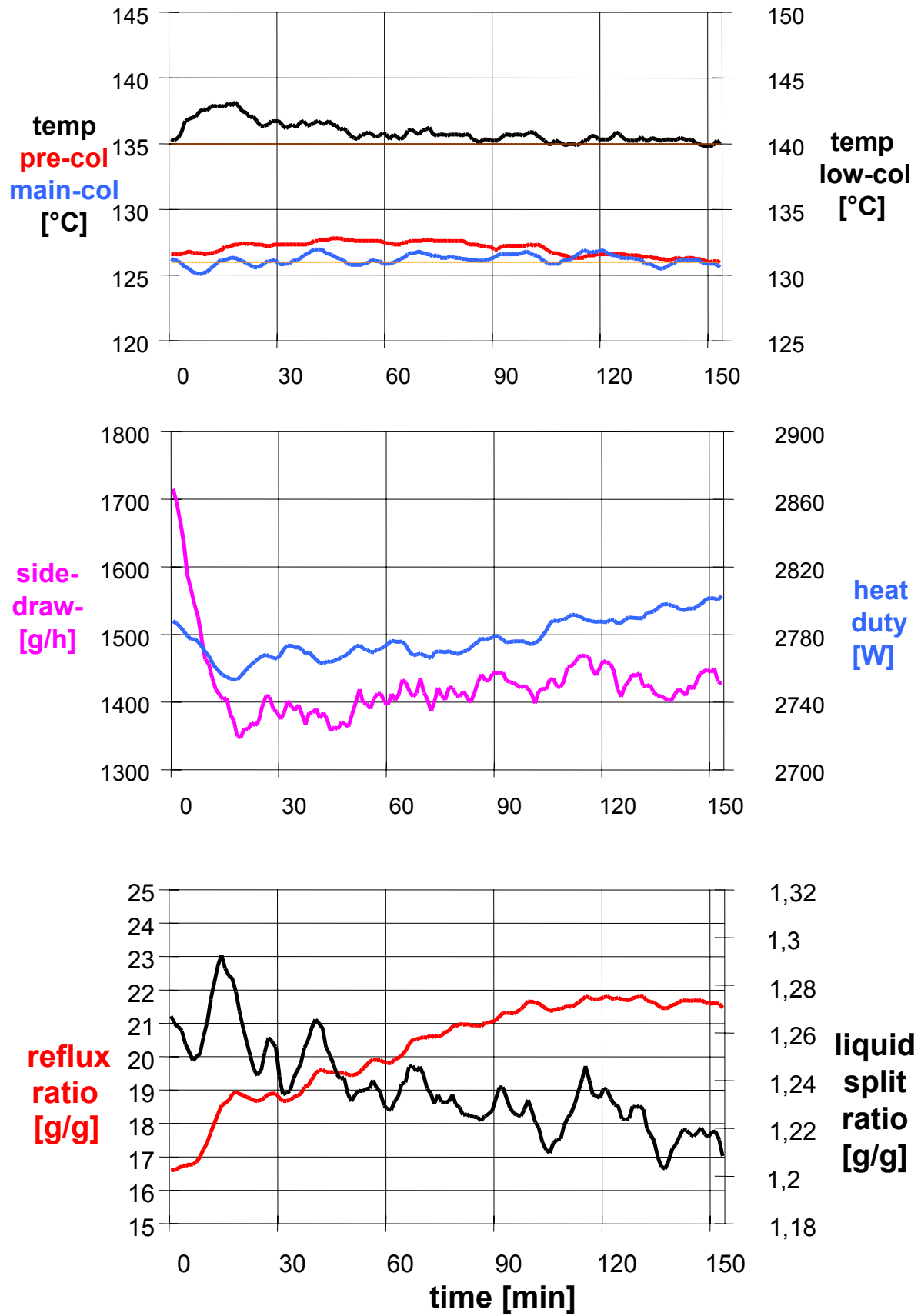


Fig.7: System behaviour for a step change in feed flow: MP controller

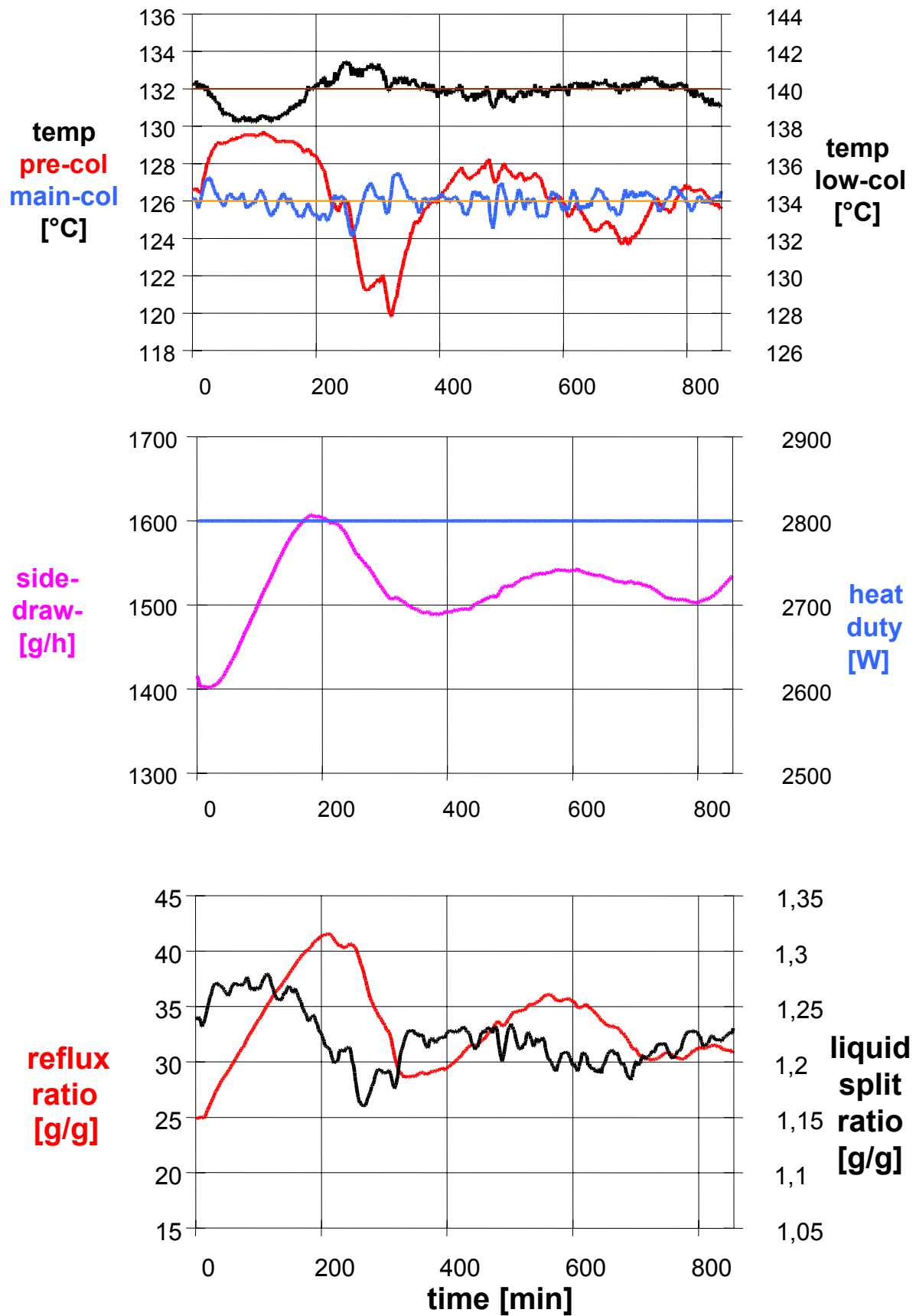


Fig.8: System behaviour for a step change in feed concentration: PI controller

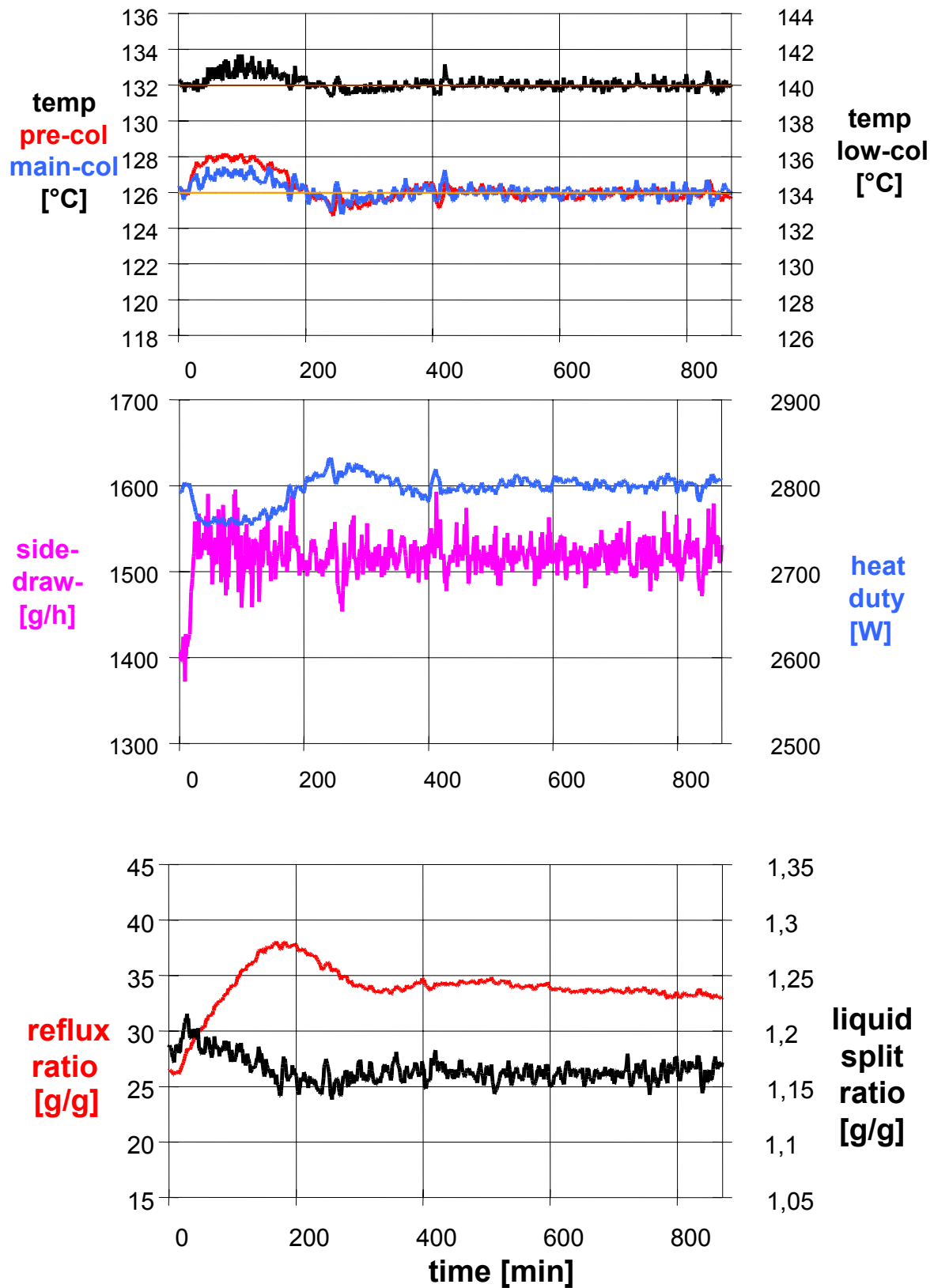


Fig.9: System behaviour for a step change in feed concentration: MP controller

The situation is different for the MP controlled system. The maximum deviation of the controlled temperatures is below 2 K. Moreover, the time to reach steady state is considerably smaller lying in the range of 3 hours. It should be noted, that for the model identification procedure, no experiments with step changes in feed concentration have been performed. However, the system is very much capable of handling these kinds of disturbances. Once again, the very fast reaction of the side draw is the main reason for this success.

CONCLUSIONS

It could be shown, that MP controllers are suitable for the control of integrated, strongly coupled processes like for example divided wall columns. Moreover the MP controller under investigation showed superior control behaviour compared to a single loop PI controller. In addition MP controllers are capable to handle constraints to keep the process away from undesired conditions. However, the effort for modelling and parameter tuning is higher than for conventional PI controllers. We estimate the effort for the MPC to be about 3 times higher than for the PI controller concept for a starting up a process with comparable complexity. The use of MP controllers should lead to considerable economical benefits if processes can be operated closer to their capacity limit and near their energetic optimal but less stable operation point.

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