ACTUATOR SELECTION BASED UPON MODEL INSIGHTS FOR AN ENERGY INTEGRATED DISTILLATION COLUMN

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A method for development of actuator structures based upon model insight is presented. The method contains three steps. First dynamic degrees of freedom are handled using suitable level actuators and control loops. Second the feasible operating region is developed and third static control structures are proposed and screened. The advantage of the three-layered strategy is that the second and third layers can be dealt with early during process development while the first layer may assure perfect control initially. Later during process design where dynamic process information is available the dynamic loops of the first layer may be designed and subsequently high level control can be designed to fit appropriate control objective for plant.

Keyword: Control, design, integrated, distillation column

1. INTRODUCTION

Chemical process plant design and operation based on combining mathematical models with computer science have the potential to significantly increase the efficiency of manufacturing systems by integrating the design with the planning of operation. Because a chemical plant may have thousands of measurements and control loops, which can be divided into several layers:

1) scheduling (weeks)
2) site-wide optimization(day)
3) local optimization/predictive control (minutes)
4) regulatory control (second)

This paper considers the local optimization layer which recomputers new set points only once an hour or so, whereas the feedback layer operate continuously. The layers are linked by the controlled variables and the selection of the control configuration, whereby the set points are computed by the upper layer and implemented by the lower layer.

Therefore it is essential to investigate operability of such complex processes at the design stage in order to enable suitable design modifications before it is too late. The systematic computer aided pre-solution analysis of process models for integrated design and control presented earlier by Russel et al. (2002) is further investigated in this paper for an energy integrated distillation pilot plant. This paper investigates aspects of design and control of the integrated distillation column with the model analysis method and validates the results through simulation and operational analysis of the energy integrated distillation column. First the steady state control configuration is obtained for column; subsequently. The dynamic behaviour of the heat integrated distillation column is discussed.

2. PROCESS DESCRIPTION

The heat integrated distillation pilot plant considered in this paper is shown in Figure 1. It contains two main sections, namely a distillation column section and a heat pump section. The heat pump section is physically connected to the distillation column through the condenser at the top and the reboiler at the bottom of the column. The heat pump consists of four heat exchangers, two compressors, one expansion valve, a large tank, α_{CV8} and α_{CV9} are the control valves. While the refrigerant circulates within the heat pump it changes phase, and through absorbing heat of vaporization at low pressure and releasing it again at high pressure it carries heat from the column condenser to the column reboiler. A more detailed description of this pilot plant is given by Eden et al. (2000). The process model analysis of these two sections is discussed individually.

3. PROCESS MODEL ANALYSIS

Model analysis first determines the available degrees of freedom for design and for control, which then identifies the "common" variables used in design as well as control. The analysis subsequently identifies the important constitutive equations, their dependent process variables and the corresponding derivative information with respect to the identified "common" variables. This analysis employs the mass and energy balance equations and the constitutive equations to generate information related to process sensitivity, process feasibility, and design constraints. The model analysis is decomposed into two parts: first the analysis is carried out for the distillation column and thereafter, the heat pump system.

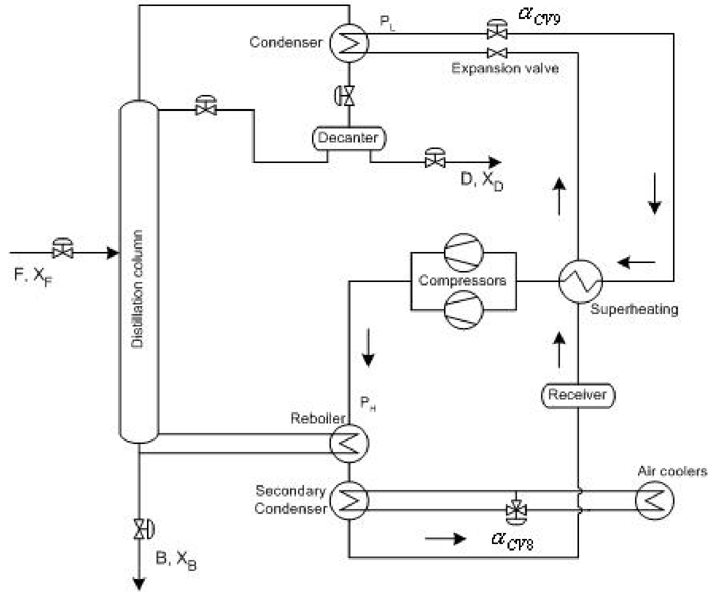

Figure 1: Flow sheet of the heat-integrated distillation column

3.1 The Process Model Analysis for the Distillation Column

Five degrees of freedom are related to five design and control variables. A design problem could be to determine the optimal values of the design variables so that some process variables attain their desired values. A control problem could be to maintain the same process variables at their desired values by manipulating the same design variables when there is a disturbance. When the design and control problems involve the same set of variables, they may be integrated and solved simultaneously, once an integrated problem has been formulated.

From a control point of view, for dual composition control of the distillation column, both the top product purity and the bottom product purity need to be controlled. The hold ups of the condenser and boiler are needed to be controlled to stabilize the system. For example the optimisation variable or design variable D (distillate flow rate) is used to control top composition x_D and vapour flow rate at the bottom V_B is used to control bottom purity x_B, where vapour flow rate is manipulated by heat duty of the reboiler Q_B. The column pressure is controlled by heat removed from the condenser Q_C. The hold ups of the condenser M_D, is controlled by reflux flow rate L_0 and the hold up of reboiler M_B is controlled by bottom product B. Hence for control purpose, the design optimisation variables, Q_B, Q_C, D, L_0, B may be chosen as the manipulated variables. This illustrates the relationship between design and control issue for a conventional distillation column.

From a design point of view, the five design variables are selected first. The product rate D and B need to be specified to meet the external mass balance and the market needs. Vapour flow rate V, the condenser heat duty Q_C and reflux flow rate L_0 are needed in the column to fulfil the separation process.

3.2 The Model Analysis for the Energy Integrated Distillation Column

From the model analysis, two degrees of freedom are obtained for the heat pump section. Here high pressure on heat pump section P_H and low pressure P_L are chosen as controlled variables. Two actuators are valves α_{CV8} and α_{CV9}.

4. OPERATION WINDOW FOR THE ENERGY INTEGRATED DISTILLATION

The appropriate variables that can be controlled through the identified “common” design/actuator variables can be identified through an investigation of the operation window. In the case of this heat integrated column with sieve trays operated primarily in the spraying regime, the limits forming the operating region are the flooding limit, weeping limits, maximum column pressure, maximum heat pump high pressure, maximum heat pump low pressure, maximum cooling power of the heat pump system, maximum pumping capacity. Inside this region is the operation window, within which the operation point must be located to ensure the separation process (as illustrated through Figure 3). The empirical correlations for flooding and liquid weeping are described below and the limits related to the high and low pressures of the compressor system are determined through simulation.

4.1 Flooding and Liquid Weeping Curves

The following derivations are based on empirical correlations estimated by several authors and collected by Zuiderweg (1982) on his review paper on the state of the art for sieve trays. Let L_0 and V be the volumetric flow rates of reflux and boil-up in m^3/s, and let ρ_l and ρ_g be the liquid and gas densities in kg/m^3. The weeping limit in terms of the minimal vapour flow rate is then found by the following empirical correlations:

$$V_{\min} = CF_w . A_t \sqrt{\frac{\rho_g}{\rho_l}} \tag{1}$$

Where: CF_{max} is the tray capacity factor on bubbling area, m/sec

A_t is the tray area, m^2

This correlation is plotted as the weeping limit, i.e. Curve 1 in Figure 3

The flooding limit in terms of the maximal vapour flow rate is used as the flowing correlation:

$$V_{\max} = CF_{\max} . A_t \sqrt{\frac{\rho_g}{\rho_l}} \tag{2}$$

Where CF_{max} is the capacity factor at start of flooding, m/sec. This correlation is plotted as the flooding limit, i.e. Curve 3 in Figure 3

4.2 Maximum and Minimum P_L

The limits of the operation region imposed by the heat pump are obtained by simulation in total reflux mode. Curve 2 in Figure 3 is mapped by switching on a controller to maintain heat pump low pressure P_L at its maximum, i.e., 600kPa and then gradually decrease high pressure P_H until intersection with the weeping limit. Going along this trajectory the number of active cylinders reduced as appropriate such that the pressure drop through α_{CV9} has a reasonable level (50-200kPa). If the pressure drop exceeds these limits retuning of the low pressure controller is necessary due to the nonlinear valve characteristic. Curve 4 in Figure 3 is mapped by keeping α_{CV9} open and all cylinders active, and then gradually decrease high pressure P_H. This way the low pressure is at all time kept as low as possible, decreasing as the high pressure is reduced. The lower limit represents the lowest possible column pressure, and it crosses the weeping limit at a point, which thus is the point of lowest possible column pressure and boil-up rate at which the column can be operated.

5. THE STATIC ACTUATOR CONFIGURATION OF THE INTEGRATED DISTILLATIO COLUMN

From the analysis of process model for the distillation column in Section 3 five degrees of freedom are obtained, which related to five design and control variables. The vapour flow and column pressure are controlled by manipulated the heat duty of reboiler Q_B and condenser Q_C. But For integrated distillation column Q_B and Q_C are not the manipulated variables, which are controlled by P_H and P_L on the heat pump section. In order to get a suitable control configuration the gain of P_H and P_L to the column pressure and vapour flow rate are investigated through simulation. The results are shown in Figure 2 from which one can see that P_H has positive gain to column pressure and vapour flow rate and P_L has positive gain to column pressure but negative gain to vapour flow rate. From this understanding it is seen that in order to increase the column pressure at constant boil-up rate one must increase both actuators, while if the boil-up rate is to be increased at constant column pressure (either P_B or P_C) one must increase P_H and reduce P_L. So it is clear that specifying the two heat pump pressures P_H and P_L is equivalent to specifying boil-up flow rate and column pressure and hence it should be possible to configure a control system manipulating the set points to the high and low pressure Through the analysis of the column the actuator structures above, it appears that P_H+P_L (on the heat pump side) is suitable to the control column pressure while P_H-P_L (on the heat pump side) may be used to control the vapour flow rate. With these control actuator configuration, the column pressure and vapour flow rate control loops are decoupled. This also means that the actuator (design) variables on the distillation column side are determined through the “control”

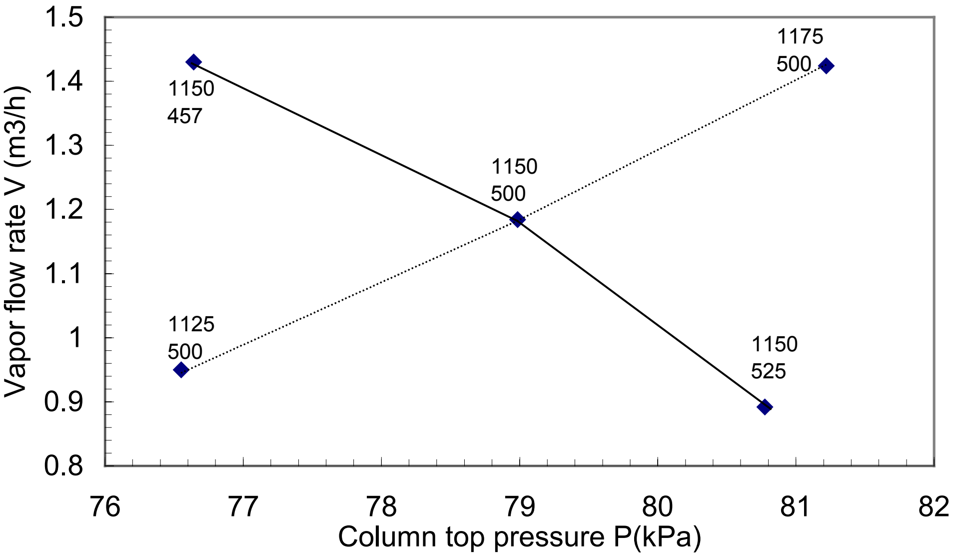

Figure 2: The gain for positive and negative changes in the heat pump pressures. Steps ±25*kPa* in high and low heat pump pressures (on simulation plot: P_H over P_L in kPa)

variables on the heat pump side. Rigorous simulations have been performed to confirm the actuators configuration with the dynamic model of Koggerbøl (1995). The simulation results are plotted in Figure 3, where the curve A in Figure 3 is at constant P_H+P_L, while P_H-P_L change. From curve A one can see that column pressure is nearly constant for constant P_H+P_L for many different P_H-P_L. From curve B one can see that the vapour flow rate is nearly the same at constant P_H-P_L in spite of different P_H+P_L. This confirms the design and control issues stated above that one could control the vapour flow rate in the integrated distillation column by manipulating the pressure difference between the high pressure and the low pressure of the heat pump side and the column pressure by manipulating the sum of the two heat pump pressures. This control structure is implemented to the column. A tool for real-time multivariable identification and control for the integrated distillation column is named Multi Input and MultI Output Selftuning Controller (MIMOSC). The basic structure of the controller is used for controlling the column pressure and the boil-up vapour flow rate. The steady state control structure is obtained for the integrated distillation column. Next paragraph a dynamic control structure is discussed .

6. CONTROL STRUCTURE FOR DYNAMIC INTEGRATED DISTILLATION COLUMN

6.1 Dynamic Control Structure for Column Section

For the distillation column, the overall control for the column section has five outputs X_D, X_B, M_D, M_B and P. Compared to the static control problem, two more holdup variables, i.e., M_D and M_B, are introduced. Suppose that the column pressure and the reboiler vapour flow have the same control configurations as the steady state. For such kind of "standard" control problem, the most widely accepted control structures are "LV-configuration" or "DV-configuration.

The issue of this kind of control configuration has been investigated using frequency dependent formulations of measures such as the condition number, the Relative Gain Array by Bristol (1966) and the Relative Disturbance Gain by Stanley et al (1985). This paper will focus on discussing the dynamic control structure on the heat pump section and how each dynamic control structure affects the stability of the integrated distillation column.

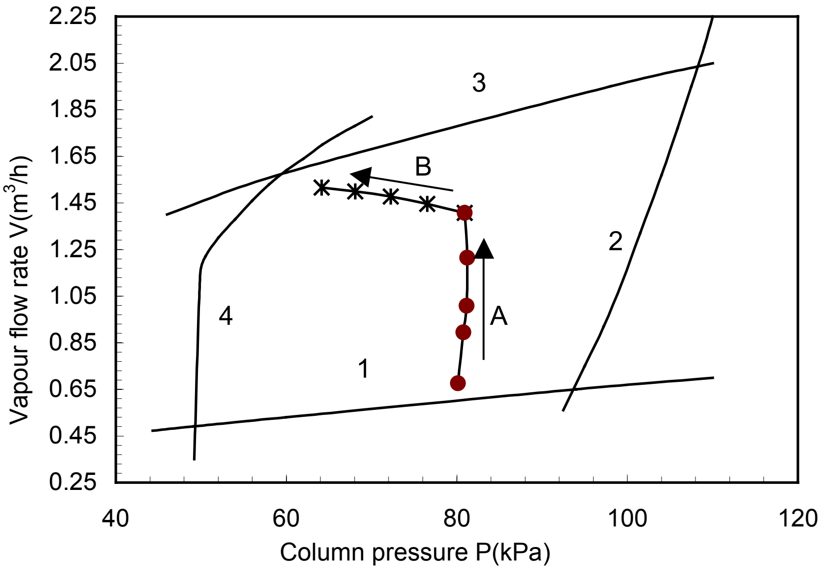

Figure 3: A curve: P_H+P_L at constant, P_H-P_L change; B curve: P_H-P_L at constant, P_H+P_L change

6.2 Control Structure on the Heat Pump Section

As discussed above, P_H+P_L and P_H-P_L are used to control column pressure and vapor flow rate. In turn, P_H and P_L are controlled by manipulating two actuators α_{CV8} and α_{CV9}. The pair of these two process variables and two control valves play a very important part in terms of stabilization of the integrated distillation column. First let us discuss how disturbance affects the heat pump high pressure P_H and low pressure P_L so as to decide the pair problems. Consider, for example, the plant at steady state with only liquid level controllers for the reboiler and the condenser has been implemented. If suddenly the energy balance is disturbed by a small amount δH, for instance due to a disturbance in the feed preheater in the feed composition, or perhaps in the temperature of the cooling medium in the secondary condenser, then the changed heat input starts to accumulate in the plant. If the disturbance reduces the cooling rate this will immediately affect the high pressure P_H such that P_H begins to increase. Thereby the compression work is continuously increased, but also the cooling rate will gradually increase as the temperature gradient in secondary condenser and in the air coolers will increase with P_H. The increase in the high pressure affects boil-up rate, and as a result of this, the column pressure and the heat pump low pressure P_L simultaneously increase. Assuming that the enthalpy of the feed remains constant after the disturbance, the behavior of the entire plant becomes unstable if the compressor work increases faster than the sum of all the outgoing heat flows. For this integrated distillation column the compressor work does indeed increase faster than the sum of all the outgoing heat flows within part of the operating region. Therefore a small disturbance in the overall energy balance can initiate a drift of the plant towards increasing or decreasing pressures depending on the sign of the disturbance. To reject disturbance so as to stabilize the system, high pressure P_H and low pressure P_L need to be controlled by manipulating suitable actuators. In theory either the low pressures or the high pressure could be paired with α_{CV8} and thereby stabilizing the system. However, the gain from α_{CV8} to the low pressures is relatively small (Koggerbøl, 1995) so if α_{CV8} is to be used for stabilization it should be preferably be paired with the measurement of P_H.

The valve α_{CV9} does not directly affect the energy balance but it can be used to stabilize the plant if it is paired with a suitable measurement. Suppose that P_L is stabilized by manipulating the valve α_{CV9} then a disturbance, which tends to increase P_L, will be neutralized by the valve opening being increased by the controller. This way P_L is maintained at setpoint. The main result of the discussion above is that high pressure P_H should be controlled and that the cooling valve α_{CV8} is preferred as actuator for this purpose. So, in conclusion, a control loop manipulating α_{CV8} based on a measurement of the high pressure P_H is suggested to stabilize the plant. The low pressure P_L is controlled by control valve α_{CV9} to stabilize the system. In the reboiler the saturation pressure P_H is a sufficient measure of the condition on the freon side for heat transport into the column, This condition is now going to be controlled using α_{CV8}. In the condenser, which is the other contact point between the heat pump and the column, the saturation pressure P_L is a sufficient measure of the condition on the freon side for heat transport from the column. So this control structures, i.e., valve α_{CV9} control low pressure and valve α_{CV8} control high pressure, can reject the disturbance and stable the system.

7. CONCLUSION

With a systematic computer aided analysis of the process model inspired by Boris et al, the control and design problems for an energy integrated distillation column are carried out. The relationships between design and control problems are discussed through analysis of the process model to result in a more suitable control actuator configuration for the integrated distillation column. Rigorous simulation results verify this analysis.

A method for development of actuator structures based upon model insight is presented. This paper addresses how to select and combine actuators in order to achieve nearly independent actuator actions. Thereby the interactions between basic control loops in the integrated distillation column are significantly reduced which is the basis for optimising control. Thereby this paper demonstrates that integration of design and control insights can lead to much more than was claimed by Russel et al. (2002).

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