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DEVELOPMENT OF A SYSTEM FOR THE DESIGN OF CONTROL STRUCTURES FOR DIVIDING WALL COLUMNS

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Abstract
The technology of dividing wall columns offers the possibility to save energy and investment costs compared to conventional distillation columns and their configurations. The practical use of the technology is still limited due to a lack of experience and high interactions between the process variables.
The contribution focuses on a new developed appliance, named *ConStruct DWC*, for the model based and automated design of control systems for dividing wall columns. The architecture of *ConStruct DWC* is explained and the effectiveness is shown by the exemplary design and test of a control system.

Keywords: dividing wall column, design of control structures, temperature control

1. Introduction

Still, distillation remains the most often used separation technique in chemical industry. Within this, the technology of dividing wall columns offers the possibility to save high amounts of energy as well as investment costs. This issue is especially valid for columns separating high purity products. Furthermore, the saving of energy is advantageous for industrial applications from ecological and economical points of view.

The complexity in the practical use of dividing wall columns results from high interactions between the process variables, from additional degrees of freedom compared to conventional distillation columns[1] and from a lack of experience. Out of this follows the importance of a suitable and practical control system. But within this, the procedure of designing a process control system is a complex, as well as iterative and interactive process and several challenges have to be solved. These can be summed up to the design and analysis of the control structure, the design of the controllers and the evaluation of the total control system. Moreover, the control system is supposed to fulfil requirements. The first aim is the stabilization of the column. Within this aspect, oscillation as well as saturation is a characteristic for an unstable operation. Then, the control system is supposed to keep the product purities constant and within their quality specification. Secondary, a control system for a dividing wall column can be used to achieve an additive objective, like an energy optimal operation. In this regard, the mentioned additional degree of freedom can be used.

Referring to the design of control structures, Figure 1 shows two sketches of dividing wall columns with possible manipulated and controlled variables. On the one hand these are the distillate stream (D), the reflux stream (R), the side stream (S), the bottom stream (B), the inlet stream (F), the heat duty of the reboiler (Q), the liquid split ratio above (LS) and the vapour split ratio below the dividing wall (VS). On the other hand these are the product purities (x_{DP}, x_{SP}, x_{BP}), the product impurities (x_{DI}, x_{SI1}, x_{SI2}, x_{BI}), the levels in the reflux drum (l_R) and the column bottom (l_B), the temperatures in the packing segments (T_C), the temperature of the inlet stream (T_F) and the top pressure (p). The applicability of these process variables for the control purpose has to be determined for each application separately. In addition, some of the named variables can not be adjusted or measured in all real applications and thus not be used for control purposes. An example is the vapour split ratio. The value of this variable is normally set automatically by the equal pressure drop on both sides of the dividing wall.

The described challenges lead to the aim and relevance of the present work. The objective is to develop an appliance, named *ConStruct DWC* (Control Structures of Dividing Wall Columns). This system can be applied for the overall model based and automated design as well as test of control systems for dividing wall columns. *ConStruct DWC* will improve the iterative and interactive design process in several aspects. First, the calculations and iteration loops are performed automatically and guided. This reduces the required development time and costs. Second, the appliance includes all required steps in a predefined sequence. Thus, all possible interactions and requirements for the respective application are considered. Third, *ConStruct DWC* elaborates, compares, analyses and evaluates different control systems. This enables to find the best control system for every application.

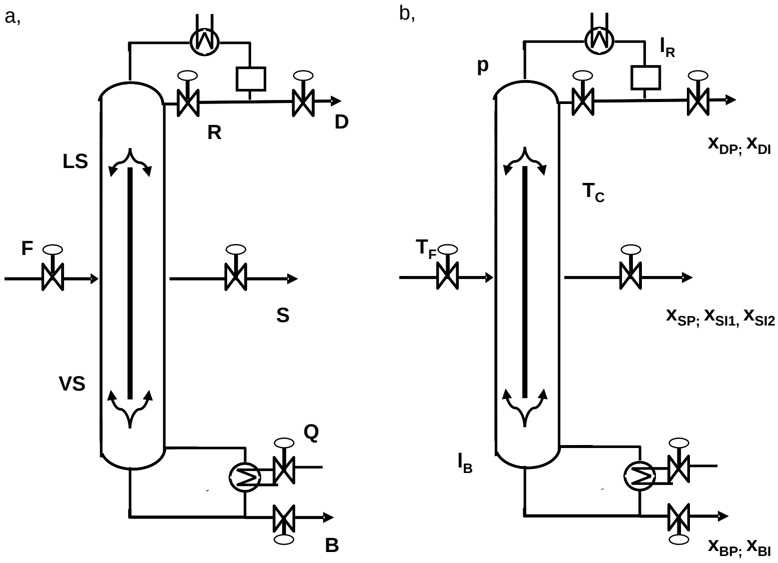

Figure 1. a, Sketch of a dividing wall column with possible manipulated variables b, Sketch of a dividing wall column with possible controlled variables

2. System Architecture

The appliance *ConStruct DWC* is mainly based on three elements: a graphical user interface, a rigorous mathematical model of a dividing wall column and several process control tools. This architecture is presented in Figure 2.

2.1 Rigorous mathematical model

One of the basic elements of *ConStruct DWC* is a rigorous mathematical model of a dividing wall column. The design of this equilibrium stage model was done by the Institute of Process and Plant Engineering[2-4], whereas adaptations and improvements are still in progress. All physical differential and algebraic equations and dependencies, which describe the separation process, are implemented in the commercial software tool Aspen Custom Modeler®. The resulting sophisticated model assures the possibility to perform extensive investigations by means of simulations. As a result of comprehensive research work, the model was validated for steady state calculations, for dynamic simulations and in particular for the simulation of the startup procedure[2]. Within this, a pilot plant is used as a reference point, first. This former validation and the additive verification for an industrial column justify the use of the model for the design of control systems for arbitrary dividing wall columns. Within *ConStruct DWC*, the rigorous mathematical model is used to predict the behavior of the investigated dividing wall column for both, open loop and closed loop operation. This means for example the prediction of dependencies, of sensitivities and of the dynamic behavior in case of disturbances.

2.2 Graphical user interface

The graphical user interface is the communication element of *ConStruct DWC*. It includes typical elements like buttons, checkboxes, popup menus and scrollbars. Furthermore, the user interface guides the applicant of the system through the iterative and interactive process of designing a suitable control system. On the one hand, this means that the user is asked to give the required input. On the other hand, this means that results and recommendations, generated by *ConStruct DWC*, are presented graphically and/ or numerically.

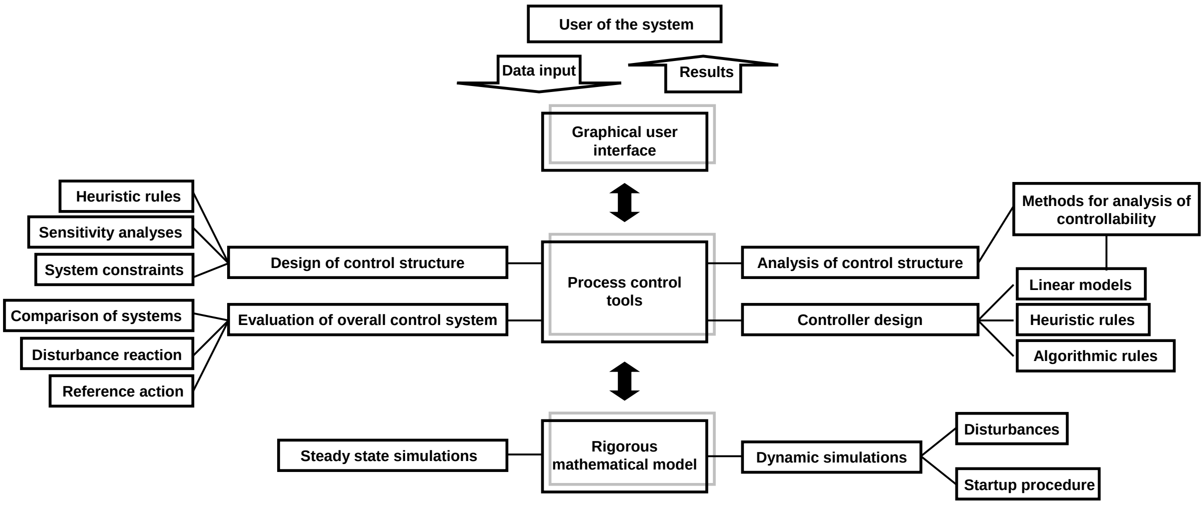

Figure 2. System architecture of *ConStruct DWC*

2.3 Process control tools

The developed process control tools have several essential functions. As shown in Figure 2 they are the core of *ConStruct DWC*. At this point the sequence in the procedure of designing a control system is defined and calculations are released. Nevertheless, the process control tools interact with the rigorous mathematical model as well as with the graphical user interface. The data exchange between the elements is done automatically for the generation of every intermediate and final result. As already described, the process control tools include several sub functionalities, which are performed independently. These functionalities are used to design and analyze a control structure and controllers. Furthermore, they can be applied to evaluate the overall developed control system.

Within this, the design of a control structure includes the definition of controlled and manipulated variables, positions of sensors, possible combinations of controlled and manipulated variables and set points. To solve this task, *ConStruct DWC* mainly uses heuristic rules, sensitivity analyses[5] and the respective constraints. The analysis of the control structure is done by methods for analysis of controllability, like the steady state and the common[6] as well as an adapted[7] dynamic relative gain array analysis. This procedure yields in qualitative and quantitative dependencies between the process variables. As shown in Figure 2 linear models are required for this issue. The generation of such linear models is especially for the highly nonlinear separation in a dividing wall column a complicated as well as iterative process. *ConStruct DWC* simplifies the procedure immense. This means that the definition of the linear operation region, the generation of the nonlinear column response, the calculation of convenient orders of the linear functions as well as the calculation of the model parameters is automated. In addition, the described procedure is done for all possible combinations of controlled and manipulated variables. This assures that definitely all dependencies are regarded in the further design.

The procedure of the controller design contains the possibility to develop parameter based controllers, like PID- controllers, as well as model based controllers, like model predictive controllers. Concerning this issue, the generated linear process models support the controller design. Furthermore, heuristic and algorithmic rules are used for the tuning. Especially for sophisticated controllers the proper tuning is essential and involves several dependent parameters, like prediction horizons and weight factors. Beside the development of suitable control structures and controllers *ConStruct DWC* offers the possibility to evaluate the generated results. That is, the control structure is tested by means of typical disturbances and by means of its reference action. Furthermore a comparison of different control systems is enabled. This assures the practicability of the results and it assures to find the best control structure for every application. Summing up, the process control tools manage the required calculations for the development of a control structure. Finally, all generated intermediate results lead to a complete designed and tested control system for the respective dividing wall column.

3. Exemplary Application

In the following the effectiveness of the developed *ConStruct DWC* is shown by an exemplary application. The objective is to design and test a decentralized temperature control strategy for a dividing wall column, which is used for the separation of fatty alcohols.

3.1 Investigated dividing wall column

The investigated example is the pilot column of the Institute of Process and Plant Engineering[4; 8]. This column is used for the separation of a mixture of n-hexanol, n-octanol and n-decanol into high purity products. It is composed of twenty theoretical stages, a reboiler, a total condenser and several collectors and distributors. Secondary, the dividing wall column is equipped with measuring devices for product streams, temperatures and the top pressure. The offline determination of the composition of the product streams is possible, as well. The investigated operating point is characterized by the data in Table 1. Referring to this, the liquid split ratio is defined as the liquid stream which is directed to the prefractionator divided by the total down coming liquid. The corresponding relation is valid for the vapor split ratio and the up streaming vapor.

Table 1. Investigated operating point

	value	unit		value	unit
inlet stream	3	kg/h	reboiler heat duty	1,31	kW
feed fraction n-hexanol	33	wt%	liquid split ratio	0,7	-
feed fraction n-octanol	33	wt%	vapor split ratio	0,45	-
feed fraction n-decanol	34	wt%	distillate purity	99,5	wt%
feed liquid fraction	1	-	side purity	99,2	wt%
feed temperature	105	°C	bottom purity	99,7	wt%
distillate stream	0,99	kg/h	top pressure	82	mbar
side stream	0,99	kg/h	top temperature	93	°C
bottom stream	1,02	kg/h	bottom temperature	152	°C
reflux stream	3,3	kg/h			

3.2 Development of control system

Using *ConStruct DWC*, a suitable control system is developed and tested for the described application. This control system is supposed to stabilize the column, to assure the high product purities and to work energy optimal. Referring to Figure 2 and the described process control tools, the control structure is designed first. Concerning this matter*, ConStruct DWC* displays three loops for the assurance of the stability of the column. That is, the top pressure is controlled by a vacuum system, the liquid level in the reflux drum is controlled by the reflux stream and the level in the column bottom is controlled by the bottom stream. To assure the high product purities, temperatures are used as alternate controlled variables instead of compositions. The reason for this is the dead time resulting from the determination of the compositions in a gas-phase chromatograph. But nevertheless, the compositions are used to supervise the performance of the control system. In the former regard, it is necessary to determine possible positions for temperature sensors in the column. Referring to the degrees of freedom and referring to three main separation regions in the column, three positions are identified to keep the high product purities. Furthermore, a position of a temperature sensor referring to an energy optimal operation is defined by *ConStruct DWC*. Then, the selected four temperature sensors are combined with the remaining possible manipulated variables. Summing up, a temperature in the upper column is controlled by the distillate stream, a temperature in the lower column is controlled by the side stream, a temperature in the prefractionator is controlled by the heat duty and a temperature in the withdraw section is controlled by the liquid split ratio (Figure 3).

In the next step the control structure is investigated by means of methods for analysis of controllability. The implemented methods, like the relative gain array analyses, show that interactions between the control loops are present, but not serious for the control purpose. Nevertheless, these interactions have to be considered in the following controller design. For this contribution parameter based controllers are developed, whereas the respective parameters of these controllers are calculated by the predefined arithmetic rules. In this case the applied method is a relay feedback test. Concerning this relay feedback test, the tuning is done automatically in several steps. This assures that the interactions between the loops are taken into account.

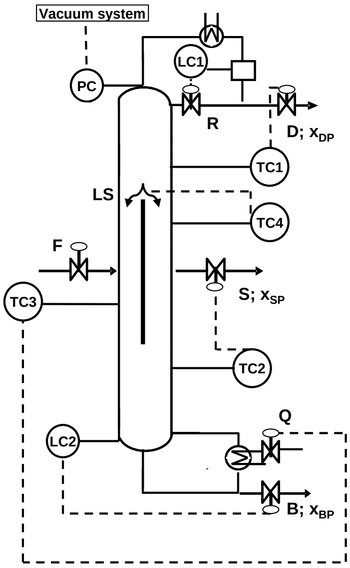

Figure 3. Process control structure for exemplary application

3.3 Test of developed process control system

The extensive test and evaluation of the developed control system is done by *ConStruct DWC* as well. In this regard the process control tools interact especially with the developed rigorous mathematical model, which predicts the behavior of the real column. Referring to the developed control system, the test and evaluation is essential for its applicability. In doing so, the necessary and extensive investigations are simplified by *ConStruct DWC*. All steps are performed automated and the user can directly apply the presented results.

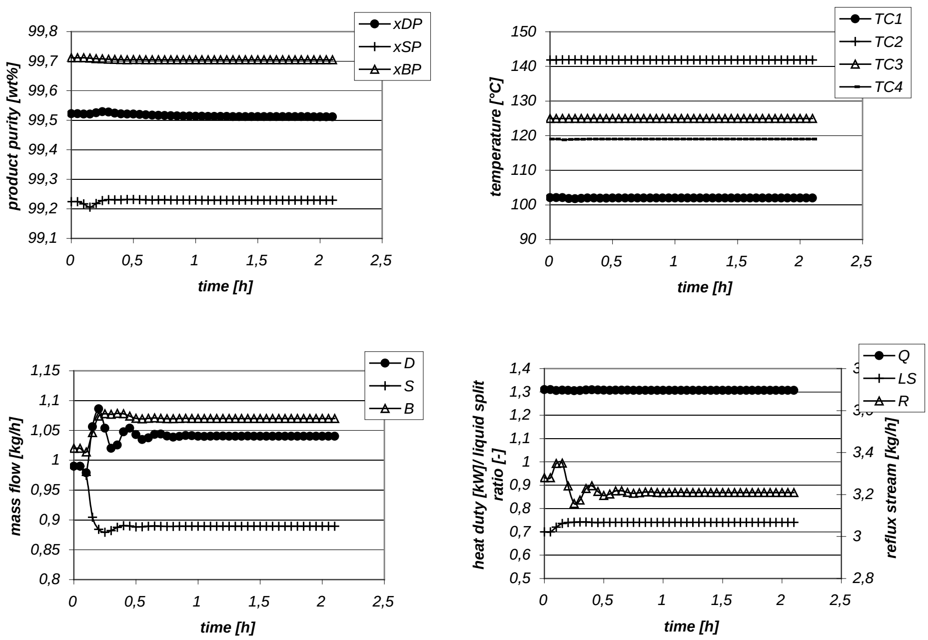

Figure 4. Product purities, controlled temperatures and manipulated variables for a step disturbance in feed stream composition

An exemplary test is the investigation of the process behavior in case of disturbances. A typical disturbance is a change in the composition of the feed stream. In the following Figure 4 the product purities, the controlled temperatures and the used manipulated variables are shown for an investigated scenario. Within this, the amount of middle boiling n-octanol is decreased by 10 wt% at a time of 0.1 h. The results show that the developed control system and thus the developed *ConStruct DWC* work very efficiently. The overall column is stabilized in a very short time and the product purities are kept constant. Consequently, the defined positions for the temperature sensors reflect the separation regions in the column. Additionally, the interactions and dependencies between the control loops are handled by the controllers very well. Eventually, in comparison to a control system which does not consider energy optimal operation and the use of the liquid split ratio as a manipulated variable the amount of required heat duty is minimized.

4. Conclusions / Outlook

A suitable and practical control system for a dividing wall column is essential for the effective use of its potentials. On the one hand the high purities in the product streams have to be assured, but at the same time the operation should be energy optimal and above all stable.

Referring to this, the design of a suitable control system is a complex, extensive and time consuming challenge. By means of the developed *ConStruct DWC* these difficulties are resolved. The described system uses three basic elements: a validated rigorous mathematical model, a graphical user interface and developed process control tools. The efficiency of *ConStruct DWC* is proven by the design and test of a process control system for an exemplary application. Furthermore, it can be summarized, that *ConStruct DWC* reduces the required time for the development of a suitable control system, it considers all dependencies between process variables and it works automated. Additionally, it guides the user through the complex procedure. Thus, *ConStruct DWC* fits the challenge of a practical appliance for the design of process control systems for dividing wall columns. In the following research work *ConStruct DWC* will be amplified. One of the future aspects is the improvement of methods for an automated development of sophisticated model based concepts (e.g. model predictive controllers) for dividing wall columns.

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