

NOVEL DISTILLATION CONCEPTS USING ONE-SHELL COLUMNS

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ABSTRACT

This presentation examines the procedures involved in implementing the divided-wall column technology for processing petrochemical cuts. Special simulation tools have been developed for the design of the overall column configuration and an evolutionary algorithm is used to find the optimum column design based on the total annual costs. Practical operation is verified on a laboratory scale with a special set of divided-wall column elements designed as a variable unit construction kit. The positive experiences and the clear economical advantages have led to industrial realisations of the new concepts in numerous commercial plants. The columns meet all expectations regarding energy consumption, product yield and purity.

INTRODUCTION

One of Krupp Uhde's fields of activity is the recovery of pure aromatics from petrochemical cuts (e.g. reformate or pyrolysis gasoline) and the reduction of benzene in gasoline in conjunction with environmental laws. In order to obtain a heart cut with a high aromatics concentration, the low and high-boiling components are separated off in a predistillation step. High-purity aromatics are then produced by processing this heart cut using the Morphylane® process - an extractive distillation process used throughout the world. Although these process steps are already highly optimised, the petrochemical industry is still seeking potentials for further reducing operating and investment costs. In this paper the implementation of the principle of thermally coupled columns will be investigated.

BASIC CONSIDERATIONS

Whenever a hydrocarbon mixture has to be cut into three well-defined fractions as in the above-mentioned predistillation step, two distillation columns are required because often conventional fractionation by one column with a side draw does not attain the purity requirements to be met by the side-draw fraction. In the classical direct sequence arrangement (Figure 1) the hydrocarbon mixture is introduced to the first column where the low-boiling fraction A is recovered as the top product. The bottom product is fed to the second column where the medium-boiling fraction B is distilled off as the top product and the high-boiling fraction C remains as the bottom product. Alternatively, the indirect sequence (not shown in Figure 1) may be applied, where the high-boiling fraction C is gained first as the bottom product. The optimum sequence is selected after consideration of the requirements to be met, e.g. the quantity of the individual fractions, the relative volatility and the thermal stability of the components, the available utilities etc., so that the investment and operating costs are kept to a minimum.

Another solution is an arrangement of thermally coupled columns as shown in Figure 1. The medium-boiling fraction B accumulates in the side column and is taken as a side draw, the purity of which can be varied as required. Compared to the previously mentioned options, the thermally coupled columns require only one heating or condensing device for both columns. In addition, the thermodynamic advantages of this arrangement over conventional fractionation, which result in lower energy requirements, have long been known.

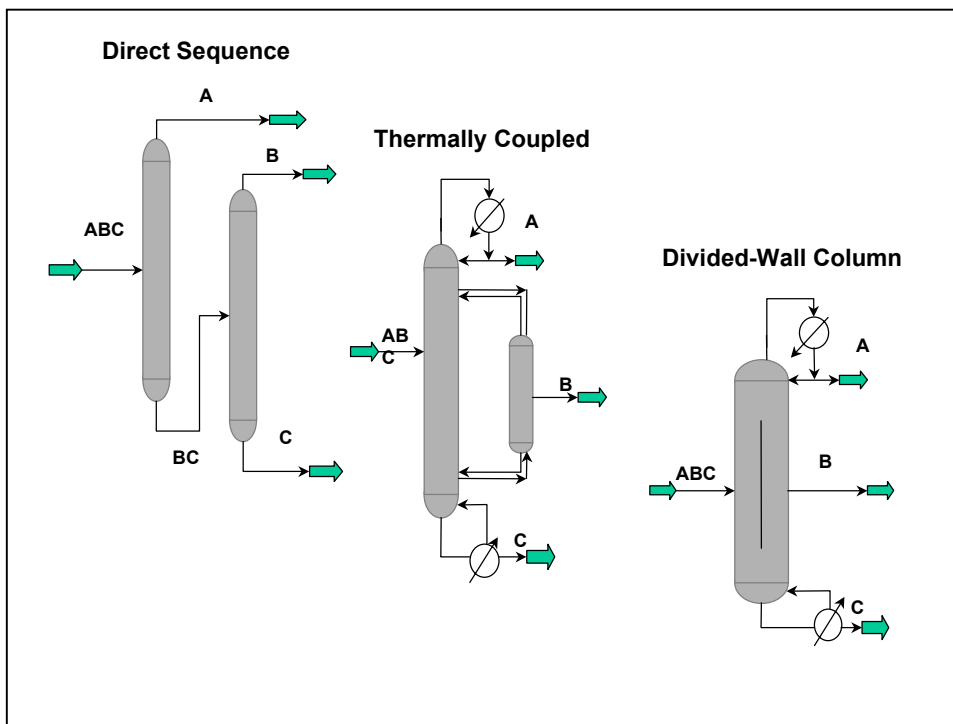


Figure 1: Different options for the separation of a mixture into the components A, B and C

A further development of the above stages is to incorporate the side column in the main column, thus resulting in considerably lower investment costs. This arrangement is referred to as the divided-wall column, also shown in Figure 1. A partition wall in the middle section separates the two columns. The energy requirements and the concentration profiles of the thermally coupled columns and the divided-wall column are completely identical.

Similarly the possibility of simplifying and cost-optimising the extractive distillation process through the application of a one-shell column arrangement is being investigated. The principle arrangement of the MORPHYLANE® extractive distillation process is shown in Figure 2.

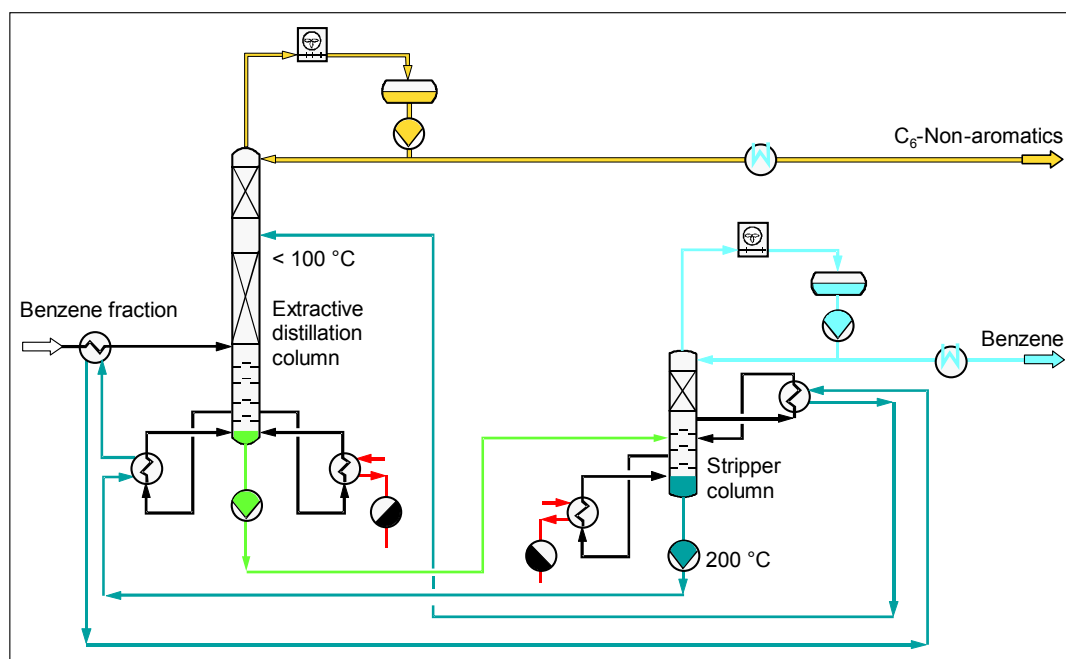


Figure 2: Flowsheet - MORPHYLANE® extractive distillation

The classical MORPHYLANE® process consists of two columns: the extractive distillation column and the stripper column (see Figure 2). The feed material, e.g. a benzene heart cut from reformate or pyrolysis gasoline, is added between the stripping and rectifying sections, and the solvent NFM above the rectifying section. The non-aromatic components are drawn off at the top of the extractive distillation column due to their highly non-ideal solution behaviour in the solvent. The aromatic fraction of the feed, which is preferentially dissolved in the solvent NFM, leaves the extractive distillation column at the bottom and is then stripped off in the stripper column. The NFM in the benzene vapours is washed back by the reflux to less than ppm level. The condensed benzene meets all industrially desired product specifications. The solvent is recycled to the upper part of the extractive distillation column from the bottom of the stripper column. Solvent traces are washed back into the solvent recovery section by non-aromatics reflux. The heat from the hot solvent is recovered almost completely by means of heat exchangers within the extractive distillation process.

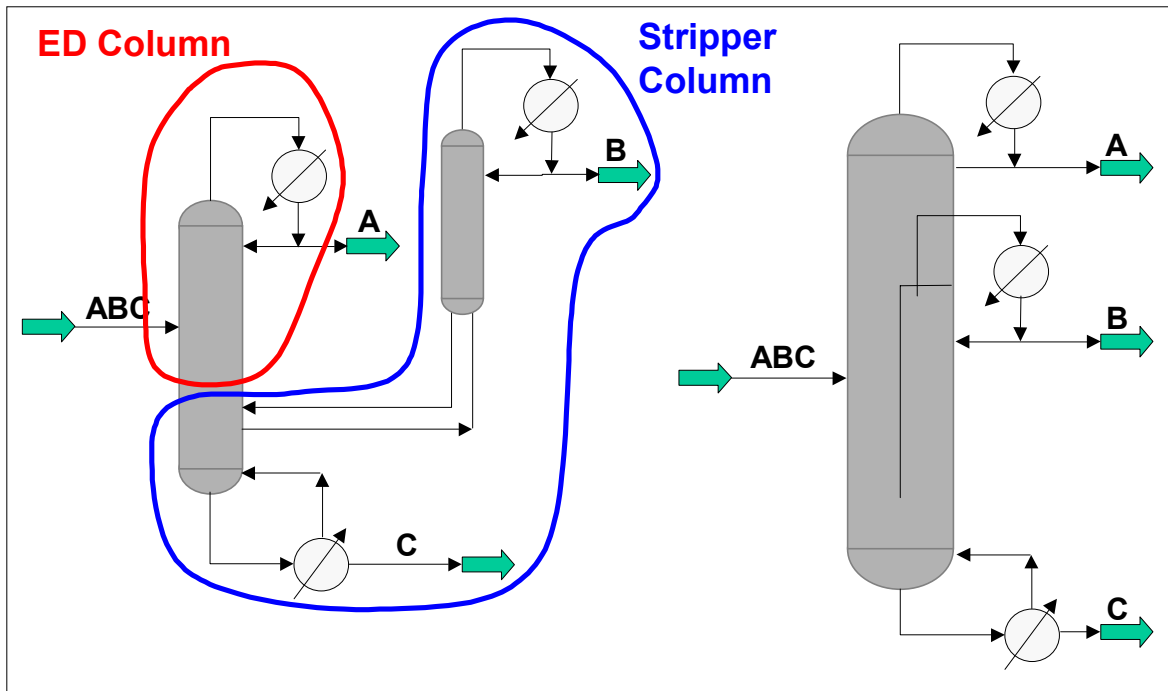


Figure 3: Single-column extractive distillation arrangement

In principle this arrangement represents merely a conventional two-column distillation system in which the low-boiling component is taken overhead in the first column, the medium-boiling component leaves as overhead in the second column and the high-boiling component accumulates in the bottom of the second column. The main difference is the fact that the high-boiling component is recycled back to the first column as solvent.

In adopting the principle of thermally coupled columns for extractive distillation, the classical two-column system is replaced by a main column with a side rectifier. The next logical step is then to incorporate the side rectifier into the column shell of the main column as in the divided-wall column shown on the right in Figure 3. A one-shell column extractive distillation configuration of this type is shown in more detail in Figure 4.

The complete column consists of 5 different distillation sections:

- I : the solvent recovery section for removing solvent traces from non-aromatics
- II : the rectifying section
- III : the stripping section
- IV : the side rectifier for removing solvent traces from aromatics
- V : the solvent stripping section

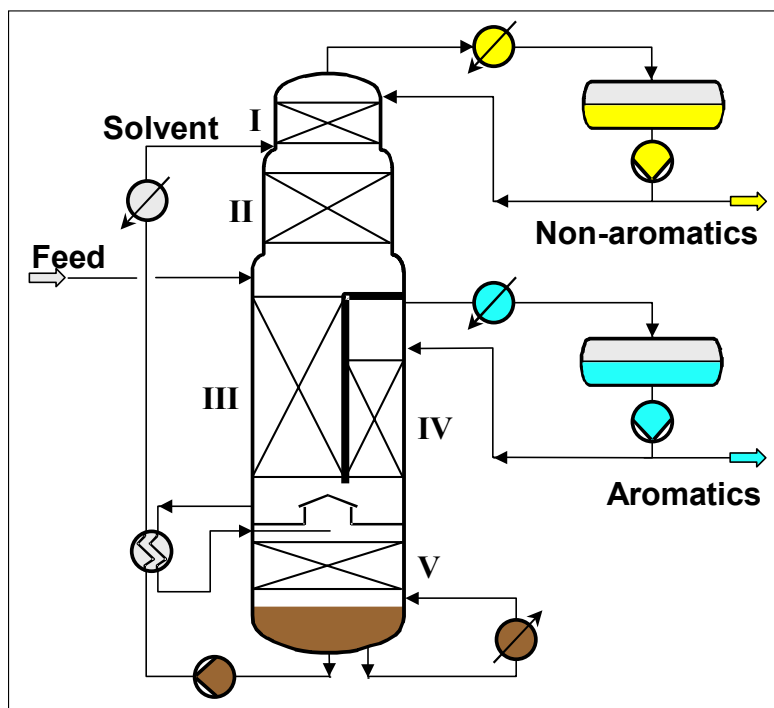


Figure 4: Thermally coupled extractive distillation

The feed material is added above section III on the feed side. The non-aromatics are withdrawn from section I, which is the solvent recovery section. When the aromatics have been stripped from the solvent in section V, the solvent is recycled to the column above section II. Intensive aromatics stripping is crucial for a high aromatics yield, i.e. the aromatics content in the solvent is drastically reduced to less than 0.1%. The aromatics product is recovered at the top of section IV once the solvent traces have been removed in this section.

The wall forms two separate chambers. The vapours which enter both sides have the same composition and their non-aromatics content must conform to the product quality for pure aromatics.

The column is equipped with two condensers, but only one externally heated reboiler. Heat integration within the column can be realised easily. A chimney tray, which directs the entire liquid through a reboiler heated with hot stripped solvent, is installed below sections III and IV.

Overall column control is an important factor in the process. The column operates under sub-atmospheric pressure. Special significance is attached to the pressure control. Small variations in the pressure difference between the two condenser systems result in variations in the vapour flow, thus supplementing the conventional control system for controlling purity and yield.

SIMULATION TECHNIQUES

Although the advantages of divided-wall columns have been apparent for decades, these columns have not been used very often in the past. One of the reasons has been their complex simulation and design. Because of faster computers and new simulation software this now no longer presents such a problem.

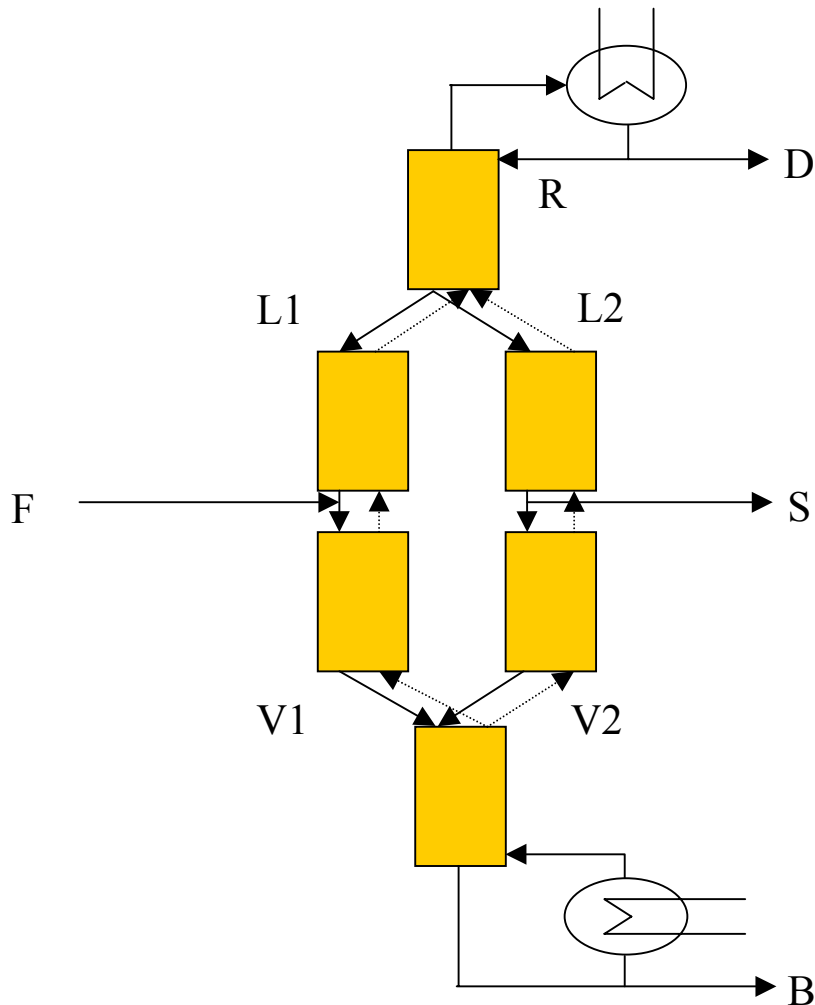


Figure 5: Degrees of freedom

Figure 5 shows the degrees of freedom relevant to the design and simulation of divided-wall columns. The following variables are unknown when starting the simulation:

Integer Parameters: - 6 column segments

Real Parameters:

- Distillate rate D
- Side draw rate S
- Reflux R
- Flow ratio L1/L2
- Flow ratio V1/V2

Commercial process simulators are not well suited to solving the task of designing a divided-wall column easily, because manual variation of the input is necessary using the commercially available software, which is rather complex and time-consuming. For a common and not sophisticated example the input has to be modified on up to nine input forms in order to change the number of theoretical stages in just one segment of the divided-wall column.

In order to enable the process engineer to optimise the design for a divided-wall column in a minimum amount of time, Krupp Uhde has developed a proprietary software interface to solve this input problem. With this interface the number of stages in each column segment can be changed easily as demonstrated in Figure 6, thus providing a process simulator input which is automatically updated with every alteration.

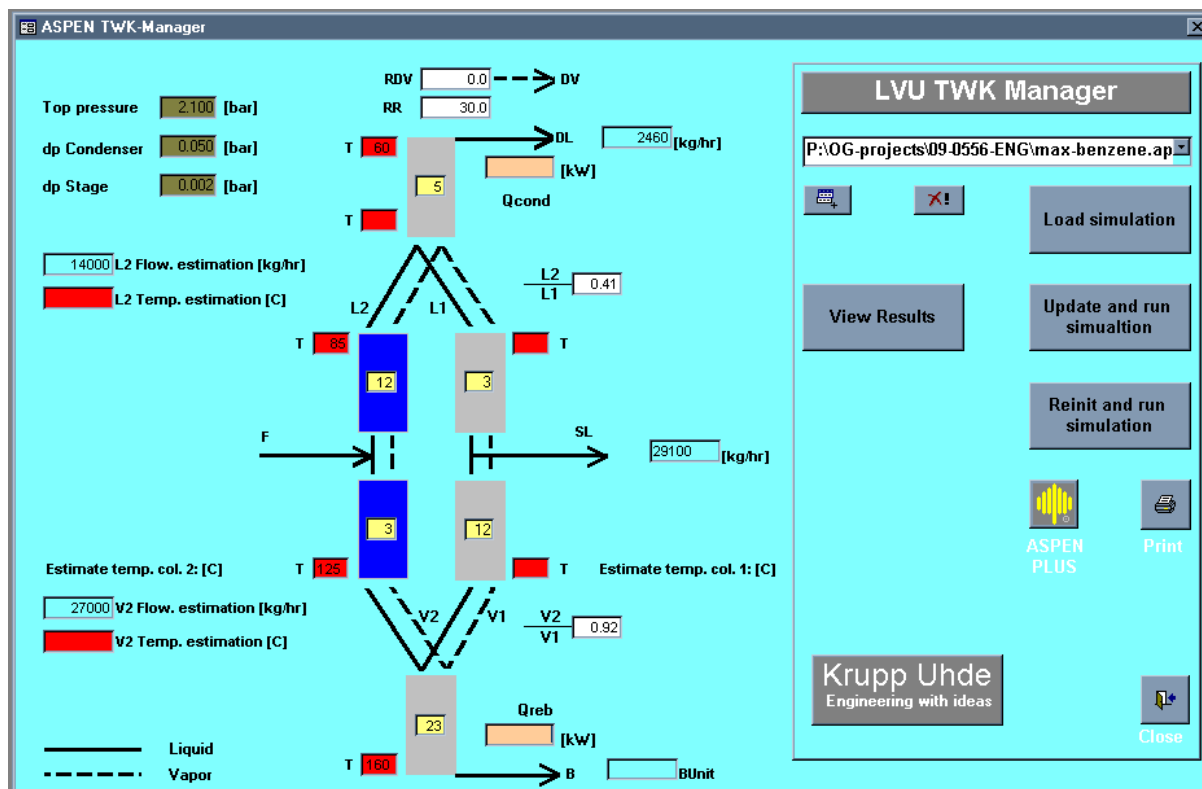


Figure 6: Krupp Uhde's proprietary software interface for the simulation of divided-wall columns

The aim of any process design is to find the most cost effective solution within the various constraints. Because of the large number of variable parameters in the design of a divided-wall column, severe convergence problems in process simulation are experienced. To overcome these problems, Krupp Uhde decided to implement an external optimisation procedure. An evolutionary algorithm proved to be best suited to solving the complex optimisation problem. Evolutionary algorithms have been commonly known for decades but, as with the simulation of divided-wall columns, their use has been constrained by the speed of computers in the past.

As in biological evolution, the optimisation algorithm produces a set of individuals, which have certain properties represented by a set of variables. The optimisation

function is calculated for each individual. After ranking the individuals, the probability for each individual's reproduction is calculated. Better individuals of course will have a greater chance for reproduction. Depending on the complexity of the system, different types of evolutionary algorithms may be preferred. Some types work with 2 parents and 6 children, others work with 20 parents and 100 children. Also different strategies are applied for selecting the best individuals, recombination, etc.

For the optimisation of a divided-wall column the above-mentioned set of 11 parameters represents an individual. Using the process simulator, utility and investment costs are estimated. These are summarised as total annualised costs for each individual. Instead of column design specifications within the process simulator, constraints are defined which determine values such as purity, recovery, etc. If these constraints are exceeded or if the process simulation does not converge, the result of the optimisation function is multiplied by a certain factor. In order to find the best individuals for reproduction, the individuals are ranked according to the annualised costs. The final result is an optimum column design which is based on the total annual costs and fulfils all constraints.

Figure 7 shows the simulation results compared to actual plant data. The data are taken from an industrial divided-wall column for the processing of pyrolysis gasoline, which was revamped by Krupp Uhde and is described in detail below. The thermodynamic behaviour of the pyrolysis gasoline is calculated by defining more than 40 characteristic hydrocarbon components in the molecular range C3 to C11 and applying the UNIFAC model. The results provide an excellent description of the behaviour of the key component benzene. The overall component split differences between the simulation results and measured plant data are in general less than 5%, though there are some components with significant deviations. This is mainly caused by the small amount of such components in the feed resulting in a large relative error, which is not decisive for the performance of the column. It should also be noted that the difference between the calculated and the actual reboiler duty is less than 10%.

Product Composition: Deviations (Actual Plant Versus Simulation)

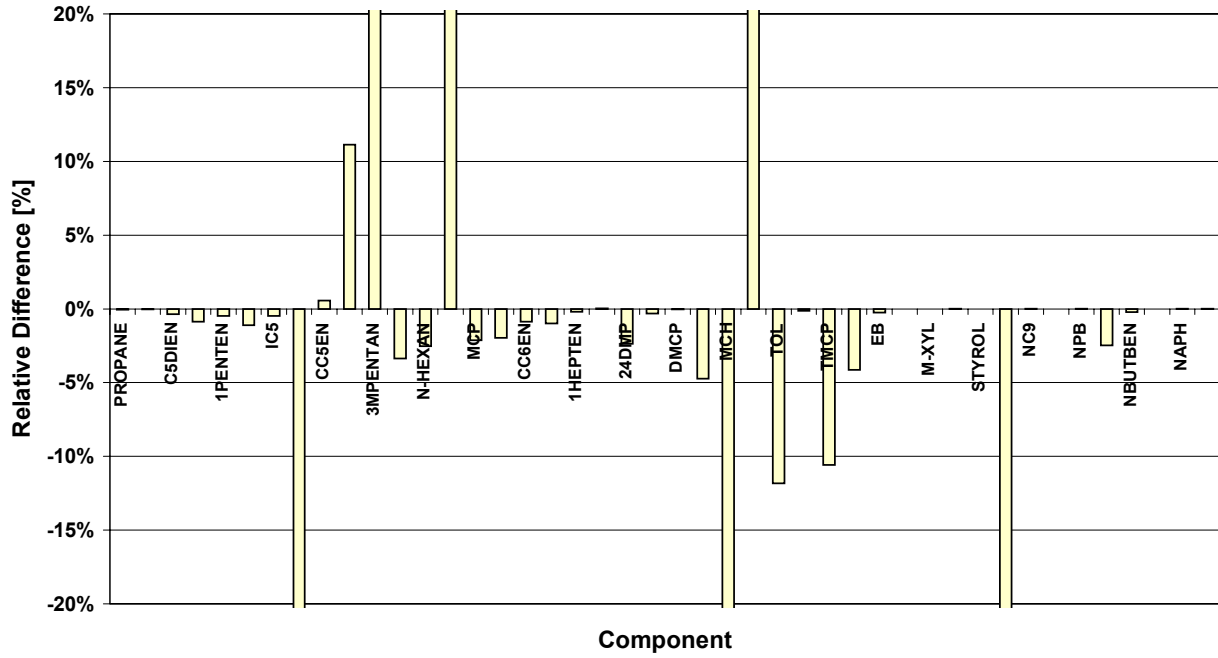


Figure 7: Relative error of the simulated component split compared to actual plant data

ECONOMIC CONSIDERATIONS

To quantify the advantages of the divided-wall column, a two-column configuration is compared with a divided-wall configuration on the basis of a commercial scale example, in this case a pyrolysis gasoline fractionation unit for benzene recovery like the one described above. The comparison was prepared during a specific project for a customer. The results are shown in Figure 8.

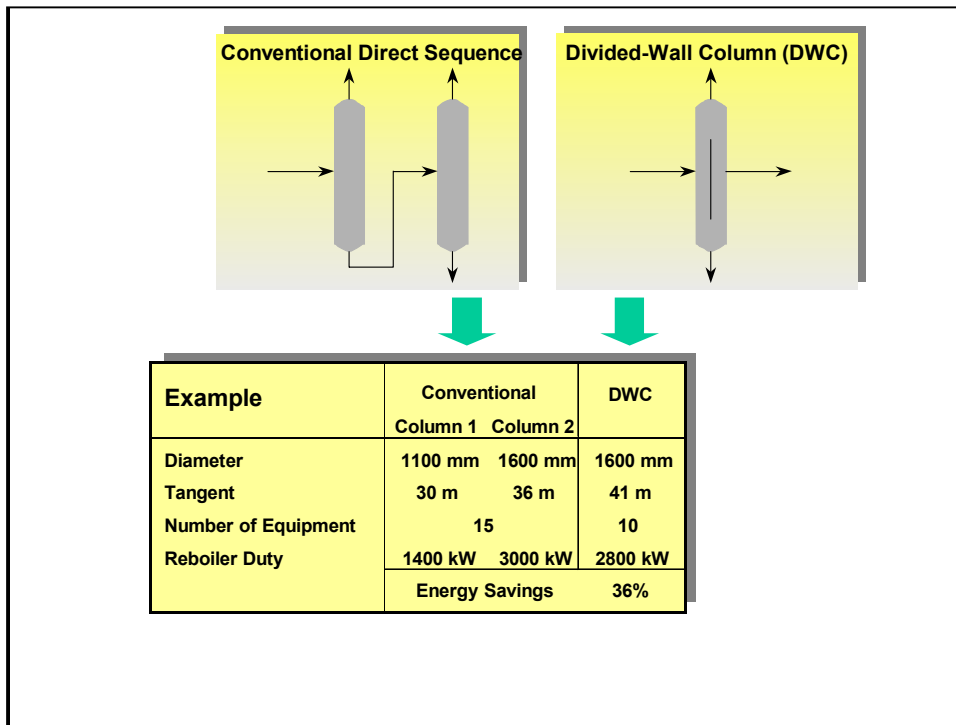


Figure 8: Performance comparison - conventional arrangement versus divided-wall column

The diameter of the divided-wall column is equal to the diameter of the biggest column in the conventional configuration. Although the height of the divided-wall column exceeds the largest column of the conventional configuration by 5 metres, the benefits of the divided-wall configuration are clear. The total number of equipment items (heat exchangers, reflux drum, pumps etc.) can be reduced by 30%, resulting in lower engineering and hardware costs. In addition, 40% less plot area is required for the divided-wall column arrangement. The resulting energy savings for this example are remarkably high at 36%, reflecting impressively the advantage of the divided-wall column technology for such applications. Based on these results the customer decided in favour of the divided-wall column over the conventional separation unit. The new column came on-stream at the end of 2000.

Figure 9 shows some general considerations on the investment cost and energy savings achieved by a divided-wall column compared to the direct distillation sequence when applied to petrochemical cuts:

- Compared with the conventional sequence the energy savings are the highest for feeds with high concentrations of medium-boiling components.

- The relative hardware cost savings (not including engineering) of a divided-wall column arrangement versus a two-column arrangement are indicated in Figure 9 as a function of plant capacity. The cost savings increase along with increasing capacity up to a maximum of approx. 20%.
- Another point, which is not considered in this graph, is the small amount of space required for the divided-wall column (savings of up to 40%)

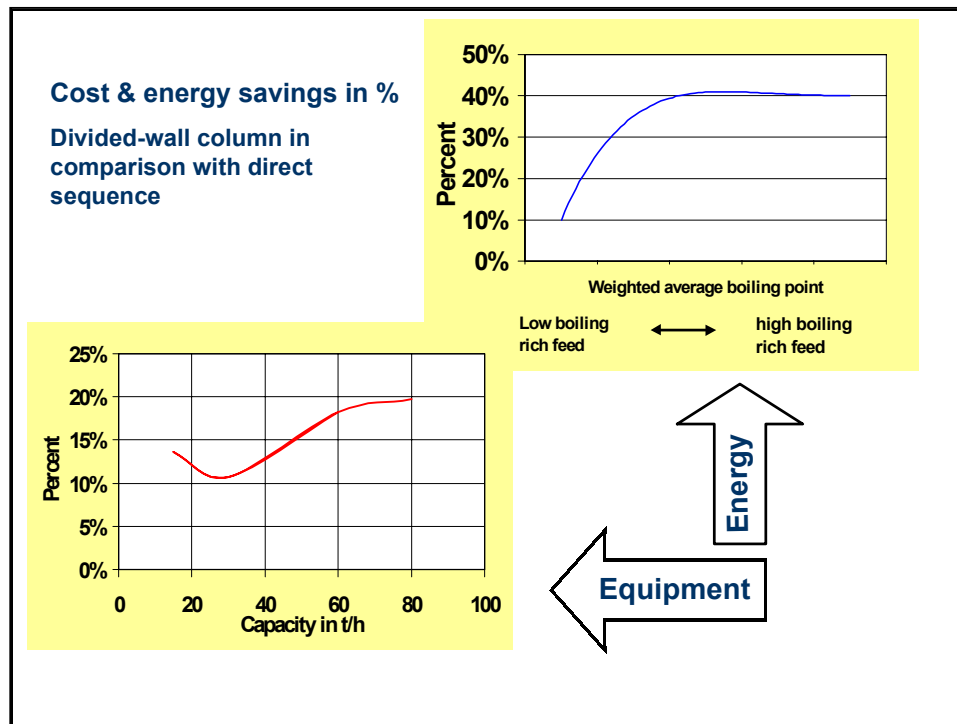


Figure 9: Investment and energy savings

Figure 10 shows the economic viability of the single-column concept for extractive distillation when applied to the recovery of pure benzene from catalytic reformat or fully hydrogenated pyrolysis gasoline. The reformat gives a lower energy saving as the percentage of non-aromatics in the feed to the extractive distillation process is higher than in the pyrolysis gasoline cut. This produces a higher percentage of top product (see Fig. 8). The final cost estimate for equipment and engineering revealed a cost advantage of approximately 20% for the new concept. This advantage is smaller than first expected, which is partly due to the lower condensation temperature at the extractive distillation head as a result of the vacuum operation of the complete system, which thus requires more condensing surface.

With respect to energy consumption, a cost saving in the steam consumption of up to 20% can be assumed. Cooling water costs are also reduced by about 10%.

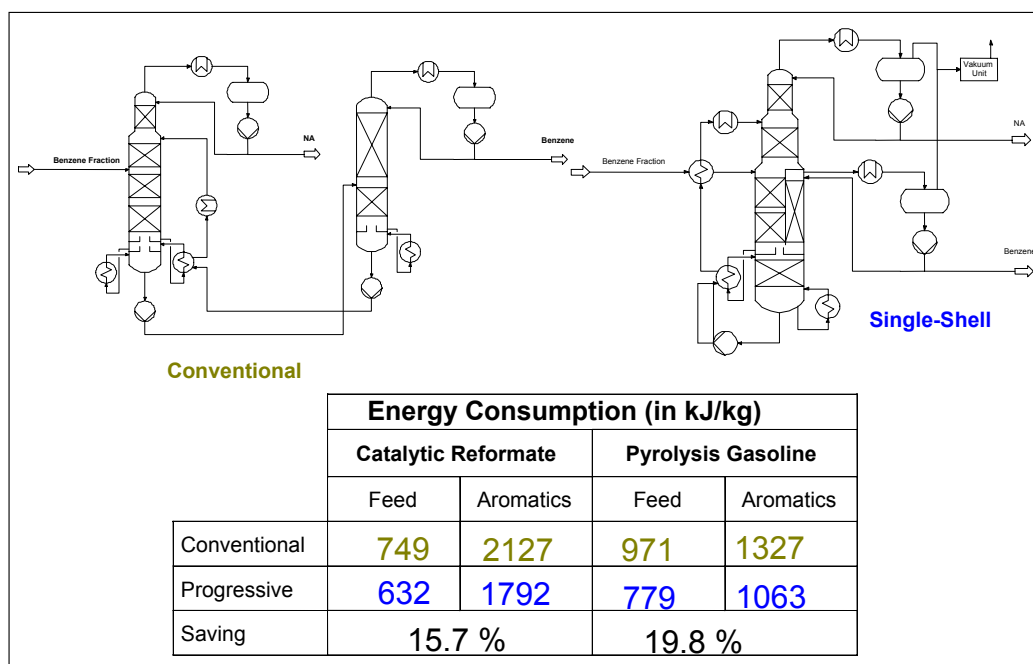


Figure 10: Comparison of concepts for extractive distillation

PILOT PLANT VERIFICATION

The development and design of divided-wall applications were accompanied by extensive pilot plant test runs. The test runs not only demonstrated the functionality and stability of the divided-wall column, but also provided the optimum solutions to details and allowed feedback for the adjustment of the simulation model.

Krupp Uhde's pilot plant is designed as a variable unit construction kit, fully connected to the lab DCS system and operated continuously 24 hours per day. The partitioned part of this column is constructed so as to allow the addition or removal of individual packing modules for selection of the number of separation stages for each side of the partition wall as necessary for each particular task. The divided-wall column element is equipped with structured packing elements, which take the form of semicircular elements and flange assemblies at the top and bottom which make it possible to add further standard column sections (modular principle). The reflux is collected above the partition and can be distributed separately to both sides of the partition wall. The distribution of the vapour to the partitions is not controlled.

Two different examples regarding special petrochemical cuts were examined: the production of a benzene heart cut from pyrolysis gasoline as a feedstock for the extractive distillation process to produce high purity benzene and the separation of a full-range reformat into a benzene, toluene and xylene fraction. The separation results of the test campaign were excellent, and all specifications were met. Taking into account the HETPs from the calibration and the heat transfer across the wall, there was a high degree of corroboration between the test results and the simulation. The operation proved to be very stable.

A pilot-scale column for the extractive distillation concept was installed with the same equipment as for the divided-wall column, but with a special internal construction for the side rectifier. The two products of the predistillation step were fed to the single-column extractive distillation unit. Figure 11 shows the temperature profile recorded on the extractive distillation side and stripper side sections of the column for one test phase compared with the simulated temperature profile. The correlation between the two profiles is extremely good, especially in the divided-wall section of the column.

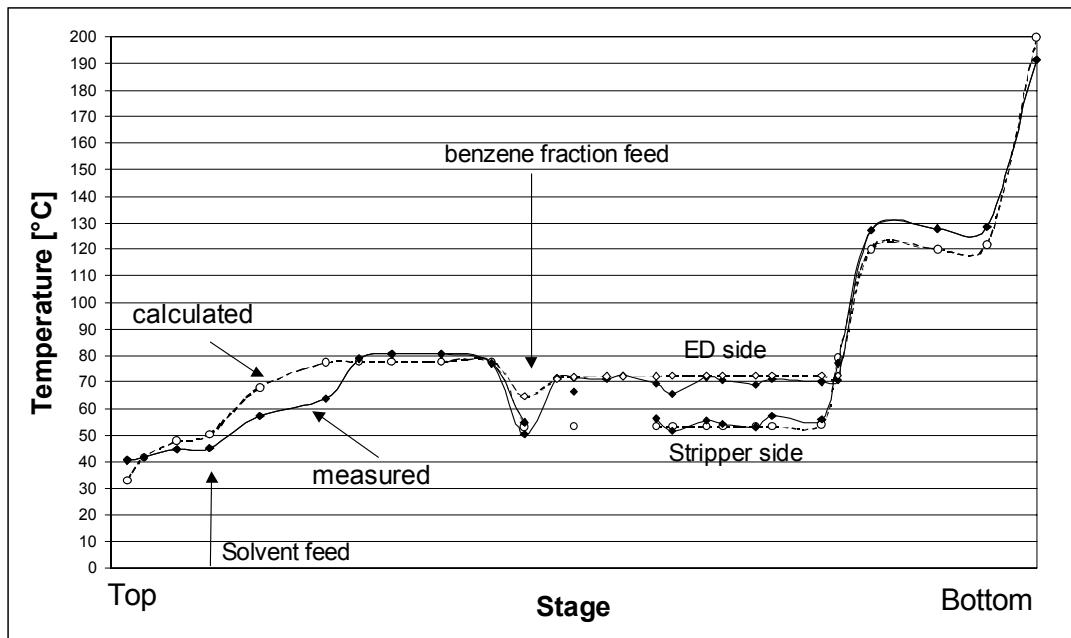


Figure 11: Temperature profiles - extractive distillation pilot plant

INDUSTRIAL APPLICATION

Krupp Uhde designed and constructed commercial plants in parallel to the laboratory investigations. As one example, the results of a revamp project of a distillation column for processing pyrolysis gasoline will be discussed. The project was mainly driven by the modified European specifications for gasoline, which limit the benzene content in the mixed gasoline (overhead product plus bottom product) to maximum 1% by volume. This task could not be achieved with the existing equipment. The benzene heart cut, gained as a side-stream product of the column, had to be concentrated as much as possible and at the same time the column's capacity had to be enhanced. The original design of the revamped distillation column included a conventional side draw for benzene removal. To increase the benzene yield and concentration in the side draw, the middle section of the column shell equipped with trays was removed. By inserting a divided-wall segment equipped with structured packing the desired separation task was achieved without altering the dimensions of the column. Figure 12 shows the column before and after the modification.

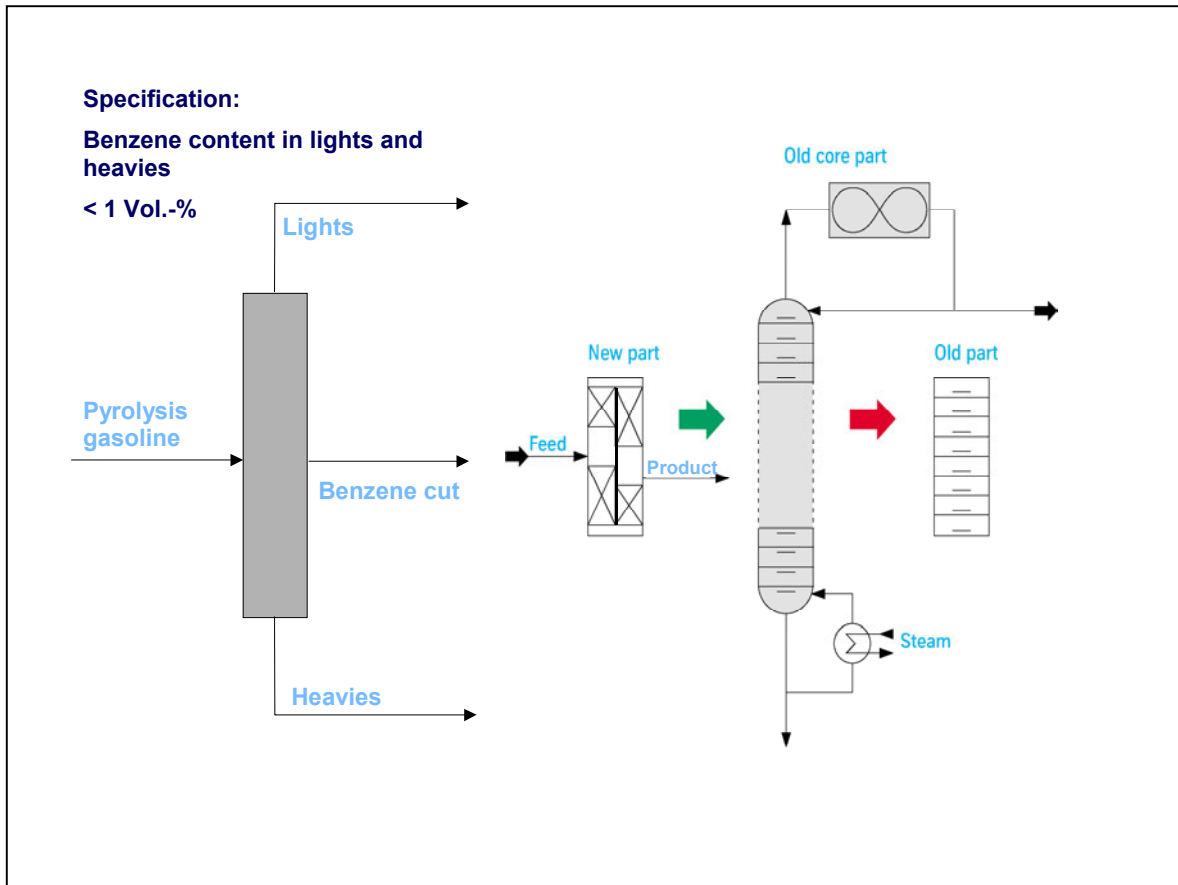


Figure 12: Implementation of the Ruhr Oel benzene removal project

The modification was planned in such a way as to allow the complete reconstruction from 'ready for opening' to 'ready for feed-in' in a plant shutdown period of only 10 days. Due to tank capacity constraints and the continuous operation of the upstream units, the realisation period for the new section had to be guaranteed. In this narrow time period the existing column shell was cut into three pieces. Part of the adjacent piping was also demolished. Then the prefabricated new column section was welded in, partly with the new prefabricated piping attached. The internals for the new section were installed and levelled on-site. Additionally, some of the pump sets were replaced to match the new debottlenecking capacity.

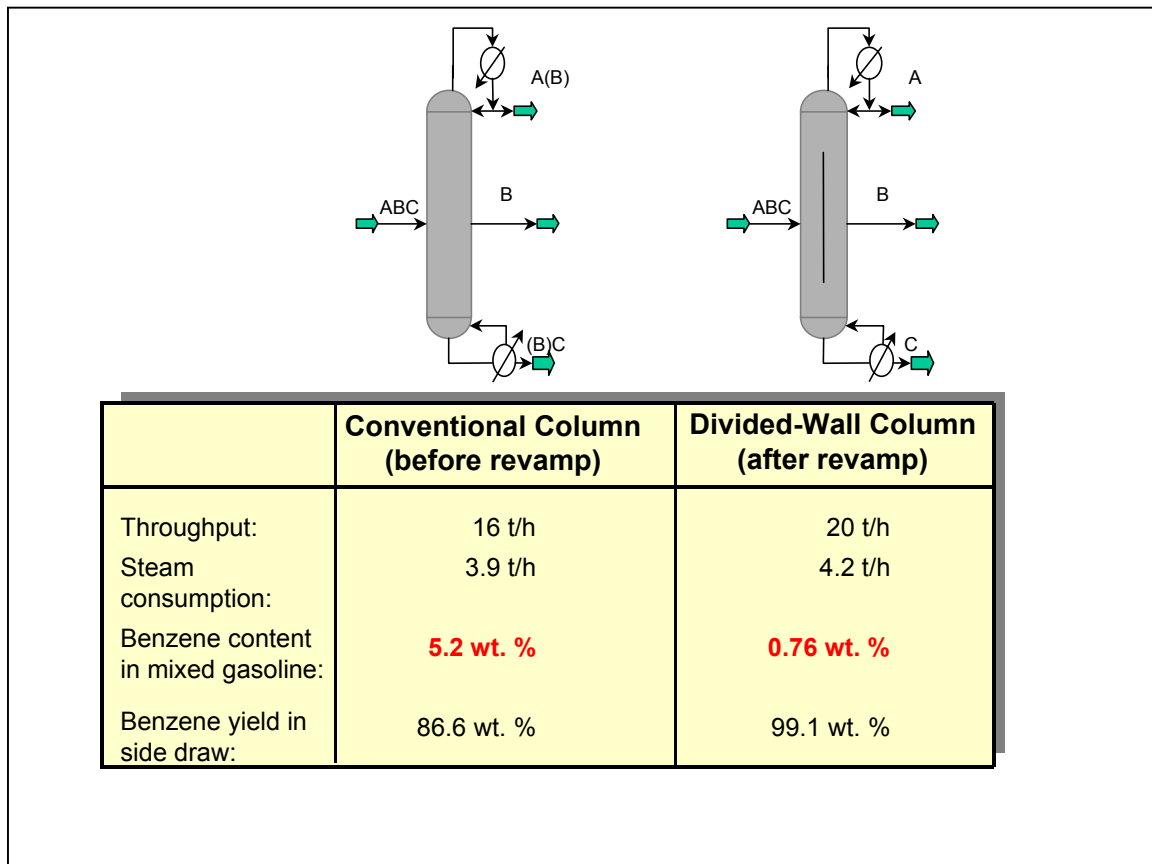


Figure 13: Performance results of the Ruhr Oel benzene removal project

The modified column was brought on stream in a record construction time of only six months from project kickoff and involved a plant shutdown period of only 9 days. It easily achieved the guaranteed performance with respect to energy consumption, product yield and purity. Figure 13 indicates the performance figures of the column before and after the modification. Despite the higher throughput of 25%, there was only an 8% increase in energy consumption after the revamp. A benzene content in the mixed gasoline of <1% by volume has been achieved in accordance with specification, and additionally the benzene yield has increased to more than 99% as a logical consequence.