Control Structure Design for Optimal Operation of 4-Product Thermally Coupled Columns

***Deeptanshu Dwivedi*[1]*, Ivar J. Halvorsen*[2]*, S. Skogestad*[1]**
[1]Norwegian University of Science and Technology, Department of Chemical Engineering, Trondheim, Norway
[2]SINTEF, Electronics and Cybernetics, Trondheim, Norway

Keywords: distillation, thermal coupling, Kaibel column, Petlyuk column

Prepared for presentation at the James R. Fair Heritage Distillation Conference,
AIChE Spring National Meeting, March 13-17, 2011, Chicago, Illinois, USA

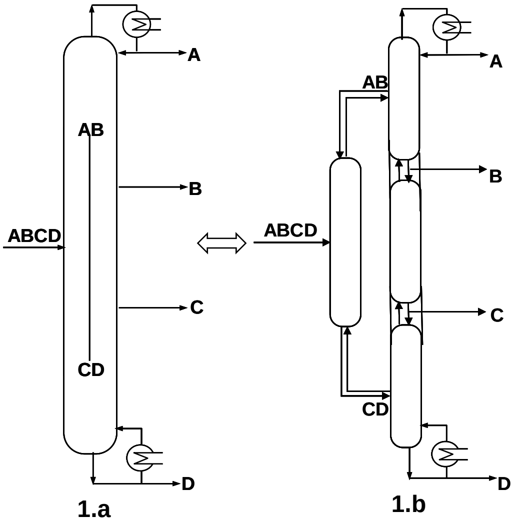
ABSTRACT

Control and operation of energy efficient complex distillation arrangements like Kaibel and Petlyuk columns can be challenging. This paper discusses the control structure design for stabilizing and operation of aforesaid systems for separating a 4-component feed namely methanol, ethanol, propanol and n-butanol as an example. The works carried out on the Kaibel column include experimental studies while the work on the Petlyuk column comprises only the simulation studies. The work demonstrates validation of proposed control structure for these two systems. Hence, provides the suggestions for operation of these designs as well as future works.

1. Introduction

Distillation is an energy intensive process. Reducing the exergy losses is one of the ways for decreasing the energy consumption. One major source of exergy losses is the mixing losses that results mainly from the remixing of intermediate boiling components at the ends of the column sections in the conventional direct or indirect split separation schemes. The mixing losses can be reduced by direct coupling of column section, often denoted full thermal coupling, leading to arrangements like Petlyuk column and Kaibel column. The potential energy saving in a 4-product extended Petlyuk arrangement can be about ~50% and 30% in the Kaibel arrangement (Halvorsen and Skogestad 2003)

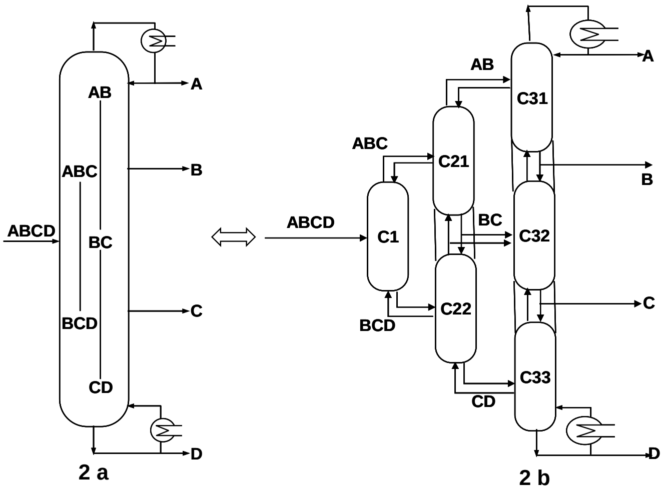
Figure 1 shows a 4-product Kaibel column (Kaibel 1987). It consists of the prefractionator where the feed enters and is fractionated with the liquid reflux and vapor drawn from the main column. It is operated such the there is a sharp B/C split in the prefractionator. The single divided wall column as originally proposed by Kaibel is equivalent to the arrangement shown in figure 1b which is similar to the experimental setup.



1.a 1.b

Figure 1: 4 Product Kaibel Column

The Petlyuk column was originally proposed for three components (Petlyuk 1965). Figure 2 shows a four product extended Petlyuk column. Here there is no sharp split and in the prefractionators, only the easiest separation is carried out; for example in section C1 (see figure 2b) only A and D is separated and the intermediates are allowed to leave in either direction of the feed tray. Again this arrangement can be in a single column shell using two vertical partition walls as shown in figure 2a(Halvorsen and Skogestad 2003),(Dejanovic, Matijasevic et al 2011).The current work discusses the control structure design and operation of these two systems and evaluates their control performance.



2 a 2 b

Figure 2: 4- Product Extended Petlyuk Column

2. Case Study 1: Four Product Kaibel Column

2.1. Background

Several simulation works have been carried out on control and operation of 4-product Kaibel column. Strandberg (2006) found that a 4-point temperature control scheme with one temperature controlled in the prefractionator coupled with the inventory control can stabilize the column and as well as prevent drift during operation. Ghadrdan, Halvorsen et al .(2011) found optimal steady state operating solutions for economic criterions like minimizing energy for fixed purity specs. Kvernland (2010) concluded that a supervisory multivariable MPC with a 4-point temperature control in the regulatory layer gives good regulatory performance. Thus there is an incentive to carry out experimental studies on operation of 4-product column. This work comprises of two sets of experiment on the Kaibel column. First, we evaluate the control performance using 4-point temperature control strategy. Next we test the efficacy of the vapor split valve (Rv). An effective vapor split valve can be used as a degree of freedom either in the regulatory layer or as an economic variable in the optimizing layer.

2.2. Control Structure used for regulatory performance

The figure 3 shows the control structure used for regulatory performance during the lab experiments. We used a decentralized PI controller. A sensitive temperature in the prefactionator is controlled with the liquid reflux split ratio (R/l) as input. The inputs: distillate (D), first side stream flow rate (S1) and second side stream flow rate (S2) are used to control three other temperature in the main column. The boilup (V) is set to a fixed value during the operation and, the vapor split ratio (Rv) that is not a part of the regulatory control structure.

The pressure of the system is self regulated by the overhead condenser. The PI loops were tuned sequentially using the SIMC rule(Skogestad 2003) and the R/l loop was closed first followed by other loops in the main column.

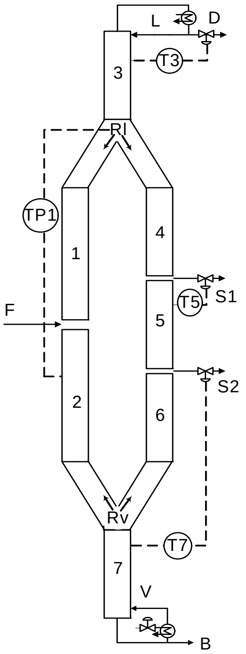


Figure 3: Control Structure used during operation of the 4- Product Kaibel Column

2.3. Experimental Set up

The experimental set up consists of about 8 meters long column operated under atmosphere pressure and is packed with 6-mm raschig rings. The liquid reflux split ratio (R/l) and the product valves (D, S1 & S2) are magnetic funnels. The vapor split valve is a rack and pinion arrangement. The total number of trays were experimentally determined and they are 17 in the prefractionator and, 21 is the main column. This number of stages is insufficient for high purity products. The control setup is implemented in Lab View™ on a standard PC.

2.4. Results and Discussion

Figure 4 shows a typical run snap shot when column run is steady for a period of 2 hours, with all the four temperature loops closed. All the four temperatures can be maintained at their respective setpoints. In figure 5, we show a setpoint change of -2C to the liquid split ratio (R/l) loop. Here, this loop controls a sensitive temperature in the prefractionator (Section 2, see figure 5). This setpoint change can be handled and the setpoint can be reached in about 25 minutes. Further there is a delay of about 2 minutes as the location of the temperature is far from the valve, and it takes a while for the change to trickle down to the controlled temperature. Further, this loop has significant interaction effects on the S1 & S2 loops. Figure 6 plots a setpoint change of ±1 C change in the distillate (D) loop. This loop controls a sensitive temperature in section 3. Again, this setpoint changes can be handled. However, there is significant interaction due to this loop on all the other loops. This is obvious because, this loop change directly the molar difference between the boil up (V) and liquid reflux (L). Figure 7 & figure 8 plot show similar setpoint changes in the S1 and S2 loops and these changes can be well handled. S1 loop controls a temperature in section 5 and S2 loop controls a temperature in section 7. However these two loops do not cause a lot of interaction on other loops. Figure 9 shows a simultaneous ±1 C change in all the four loops.

Simulations confirm that, with the given number of stages in the system, high purity products are impossible. There are no online measurements. Samples were taken out from the system during runs. Top and bottom product were 95 % pure, while the purity of the side products, S1 was up to 60% and of S2 was up to 85% only.

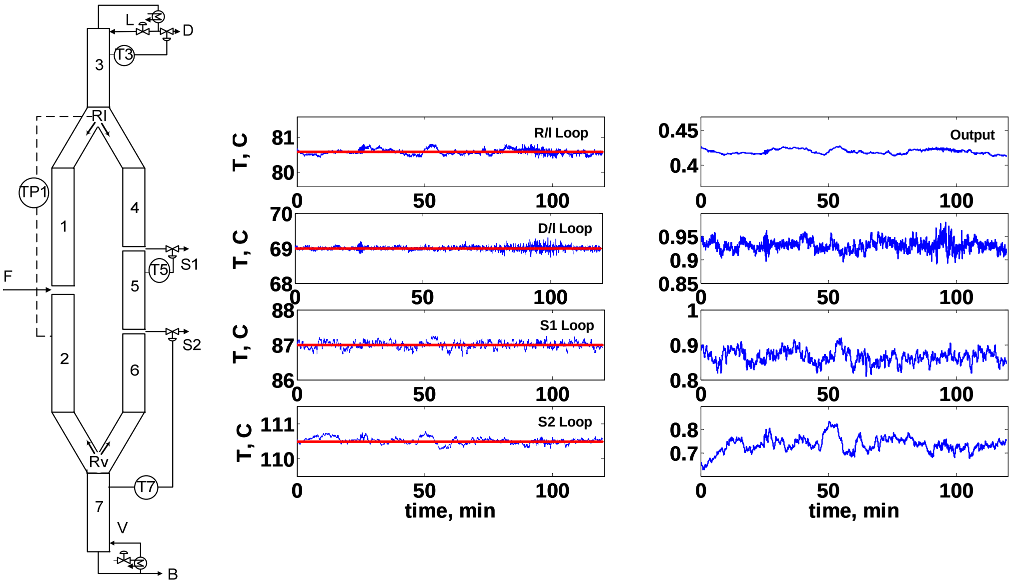


Figure 4: Four Product Kaibel column: All loop in Auto

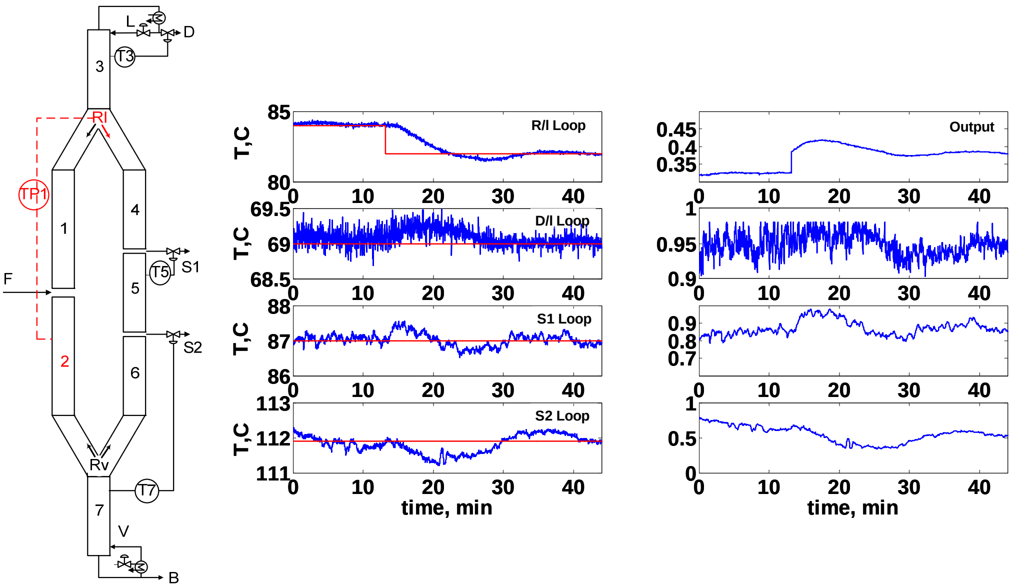


Figure 5: Four Product Kaibel column: All loop in Auto; R/I loop -2 C setpoint change

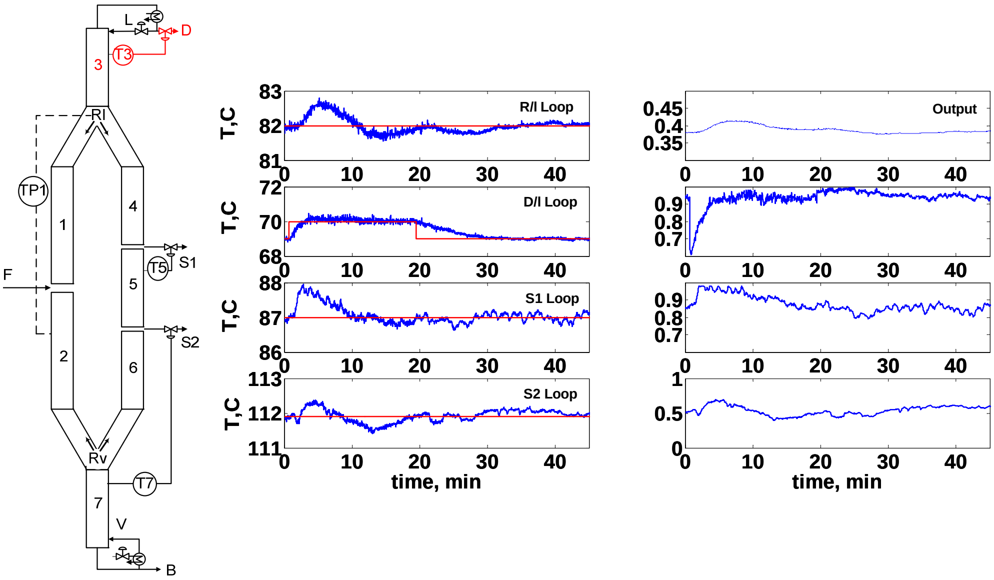


Figure 6: Four Product Kaibel column: All loop in Auto; Distillate loop ±1 C setpoint change

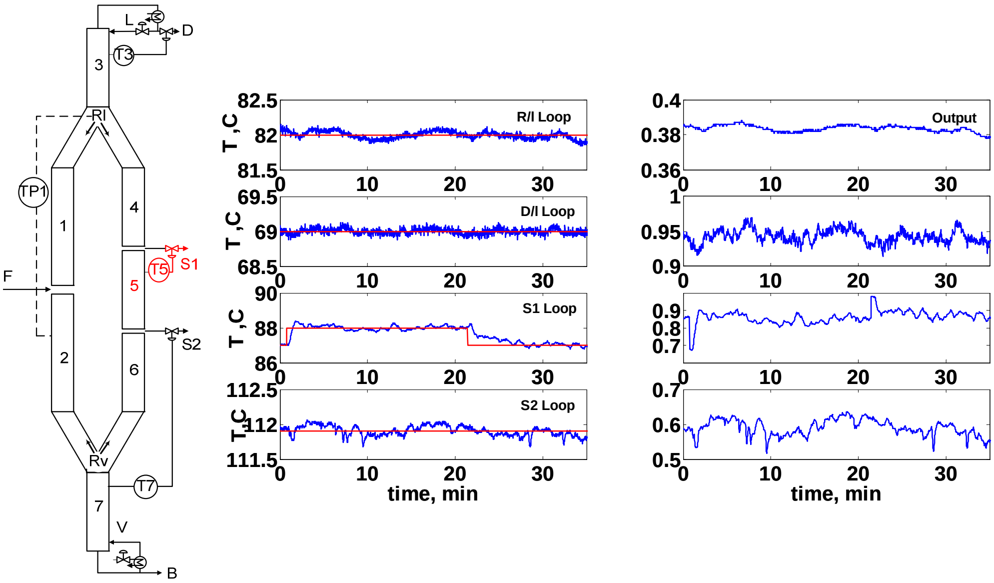


Figure 7: Four Product Kaibel column: All loop in Auto; S1 loop ±1 C setpoint change

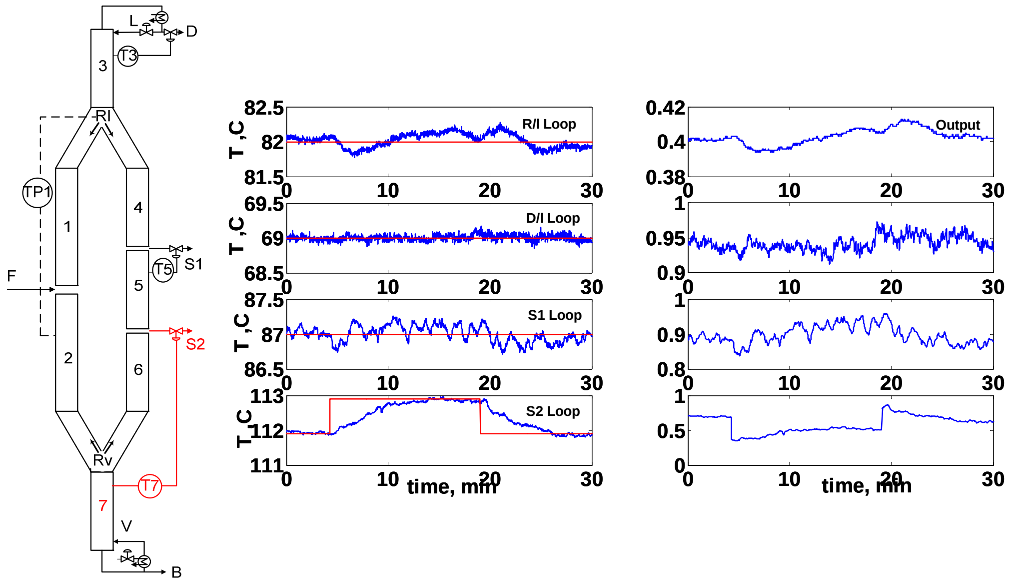


Figure 8: Four Product Kaibel column: All loop in Auto; S2 loop ±1 C setpoint change

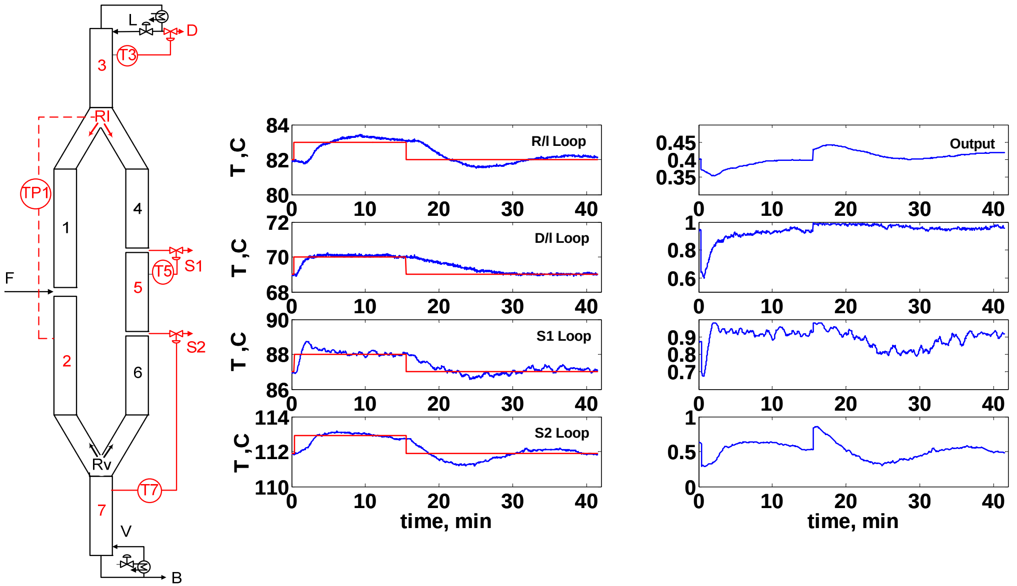


Figure 9: Four Product Kaibel column: All loop in Auto; All loops ±1 C setpoint change

2.5. The Vapor Split Experiment for the 4-Product Kaibel Column

This experiment is carried out to study the efficacy of the vapor split valves. The vapor split valve is a rack and pinion arrangement as shown in the figure 11. A motor moves the valve in the vertical axis to operate it. It is obvious that the resolution of the valve is good for only small openings. But control can however be done with a feedback action. Better designs for doing this split effectively, can be proposed and should be an area of interest for the valve specialists.

In this experiment only methanol and ethanol was used in the laboratory setup and the column is operated in total reflux condition. The liquid split valve is kept in the manual condition. The manipulated variable is the vapor split valve and the controlled variable is the difference between a temperature in section 2 and a temperature in section 5. This vapor split valve has the split range

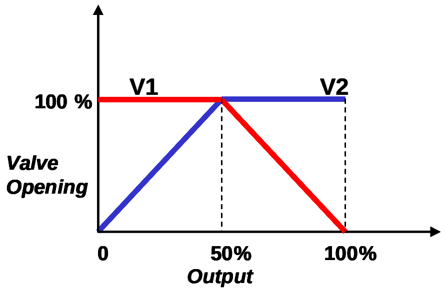
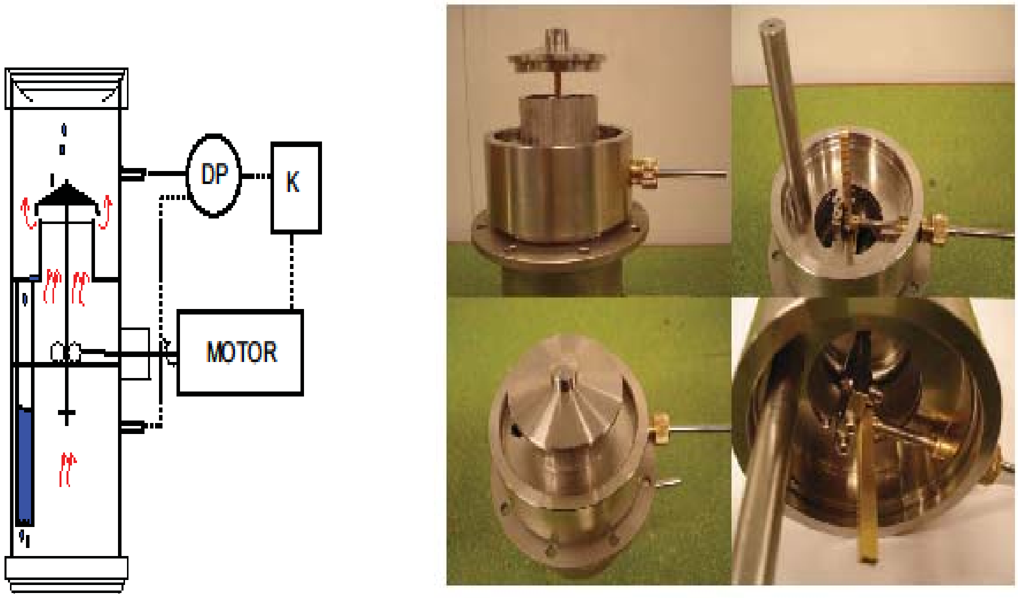


Figure 10: Split range logic for the vapor split valve control

logic (see figure 11). When the output of the controller is 0.5, both the valves are fully open. For any other value of the output of the controller, one of the valves is fully open and only the other valve is operated.

Figure 12 shows the control structure used for this experiment and the experimental run. The vapor split valve here, sets a difference between one temperature in the prefractionator section 2 and section 5. These setpoint changes can be handled. The regulatory response of the same is good, when the reboiler duty is increased by 10% at about 100 minutes.



Schematic of the vapor split valve

From top left: Valve in fully open position
Top right: Rack and pinion arrangement.

Figure 11: Schematic and picture of the vapor split valve

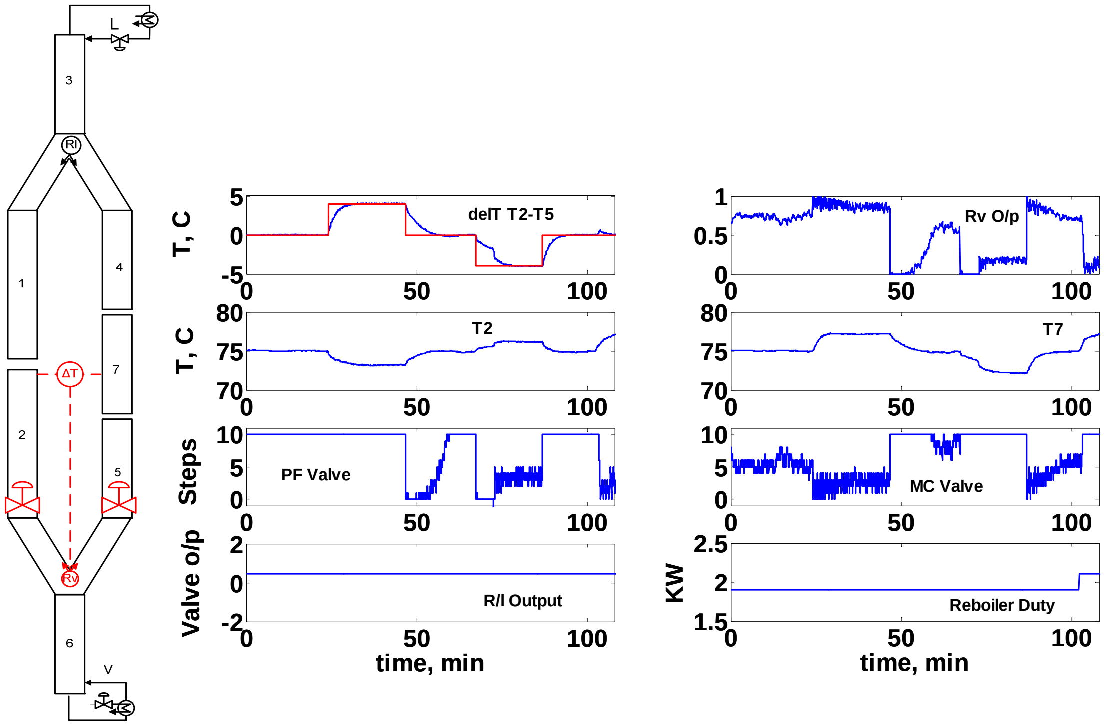


Figure 12: Kaibel column: Vapor Split Experiment

3. Case Study 2: Four-Product Extended Petlyuk Column

A dynamic model of a four-product extended Petlyuk column as shown in figure 2b is developed for the work. The model uses simplified thermodynamic assumption of ideal vapor liquid equilibrium, constant relative volatility model and constant molar flows in sections. Large numbers of stages (40 stages) were assumed in each column section. The column flows for the purpose of simulation are initialized by the V-min diagrams (Halvorsen 2003). V-min diagrams give analytic solution of minimum vapor/ liquid reflux required by solving the Underwood equation(Underwood 1949).

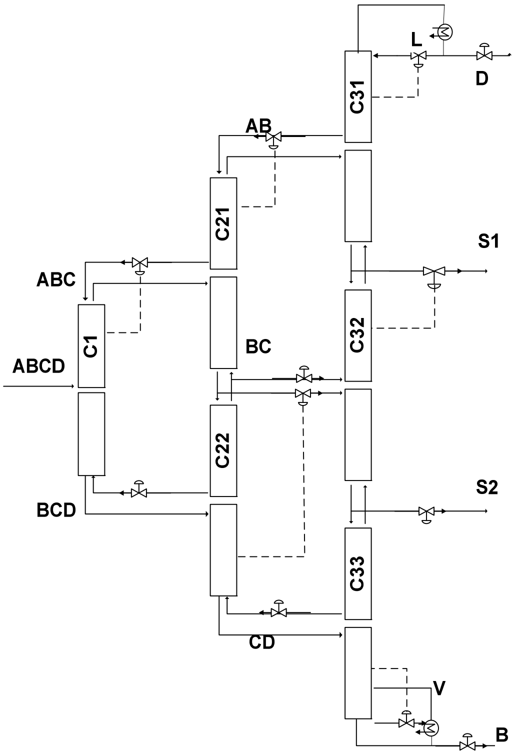


Figure 13: Control Structure used in 4-Product Extended Petlyuk Column

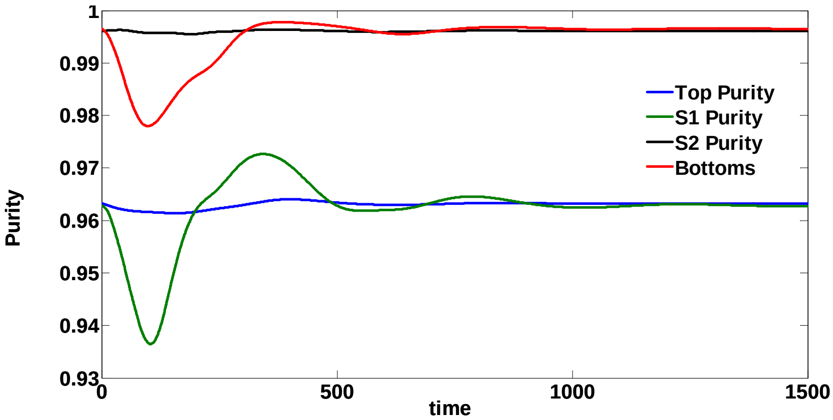


Figure 14: 4-Product Extended Petlyuk Columns: Regulatory Response for 10 % increase in Feed Flow rate

Figure 13 shows the control structure used for the work. Six temperatures were controlled in the regulatory layer. All loops were tuned sequentially from left to right using the SIMC rules(Skogestad 2003).
Figure 14 shows closed loop results for a +10 % feed change. We notice a good regulation and that the purity of all the components can be controlled well using this control structure.

4. Conclusions and Future Work

Experimental studies confirm stable operation with 4 point temperature control of the 4 – Product Kaibel Column. A lab scale prototype of vapor split valve effectively controlled vapor flow between prefractionator and main column. There is a scope for improving the vapor split valve as the used valve gives resolution for only very small openings of the valve and for industrial scale up, more innovation is required. Nevertheless, even with this rather simple prototype valve, experimental results show that the vapor split can be manipulated effectively in feedback mode to stabilize the prefractionator temperature profile.

Preliminary simulation studies suggest that a 4-product extended Petlyuk column can be operated with 6 point temperature control in the regulatory layer. A more rigorous controllability analysis by simulations and experimental studies should help in the providing more insights for operating thermally coupled columns.

5. References

Dejanovic, I., L. Matijasevic, et al. (2011) "Designing four-product dividing wall columns for separation of a multicomponent aromatics mixture." Chemical Engineering Research and Design **In Press, Corrected Proof**., doi: 10.1016/j.cherd.2011.01.016

Ghadrdan, M., I. J. Halvorsen, et al. (2011)"Optimal operation of Kaibel distillation columns." Chemical Engineering Research and Design **In Press, Corrected Proof**. doi: 10.1016/j.cherd.2011.02.007

Halvorsen, I. J. and S. Skogestad (2003). "Minimum Energy Consumption in Multicomponent Distillation. 3. More Than Three Products and Generalized Petlyuk Arrangements." Industrial & Engineering Chemistry Research **42**(3): 616-629.

Kaibel, G. (1987). "Distillation columns with vertical partitions." Chemical Engineering & Technology **10**(1): 92-98.

Kvernland, M. H., Ivar J.; Skogestad, Sigurd (2010). Model Predictive Control of a Kaibel Distillation Column. DYCOPS 2010 Leuven, Belgium, IFAC, Dynamics and Control of Process Systems. **9**.

Petlyuk, F. B., Platonov, V.M. and Slavinskii, D.M. (1965). "Thermodynamically optimal method for separating multicomponent mixtures." International Chemical Engineering **5**(3): 555-561.

Skogestad, S. (2003). "Simple analytic rules for model reduction and PID controller tuning." Journal of Process Control **13**(4): 291-309.

Strandberg, J. S., Skogestad (2006). Stabilizing operation of a 4-product integrated Kaibel column. INSTITUTION OF CHEMICAL ENGINEERS SYMPOSIUM SERIES, Institution of Chemical Engineers; 1999. **152:** 636-647.

Underwood, A. J. V. (1949). "Fractional Distillation of Multicomponent Mixtures." Industrial & Engineering Chemistry **41**(12): 2844-2847.