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Limitations of Air/Water Testing in the Development of High Performance Trays

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Retrofitting distillation columns with higher capacity mass transfer internals is an effective way of increasing productivity. In the last decades, tray research and development has focused on two areas – improvement of downcomer designs and development of high performance valves with the target to handle higher vapor loads. An example for the second approach is the development of the new Sulzer UFM™ valve. This paper discusses Sulzer's experience with laboratory testing strategies for fractionation trays and limitation of hydraulic tests with water and air.
Air/water testing is very popular due to the low cost and its simplicity. It is still considered as a reliable starting point for screening design options and to evaluate feasibility and capacity. The beginnings of the Sulzer UFM valve development followed this path, but soon weaknesses of the air/water test system were found. Prototype designs preceding the Sulzer UFM valve showed very promising results. Consequently, they were further optimized using air/water for maximum hydraulic capacity. But subsequent distillation tests using a standard binary test system at total reflux could not confirm previous findings. A reduction in liquid entrainment, as observed with water, does not necessarily lead to a capacity increase in distillation. The chosen testing strategy was obviously not efficient and disadvantageous regarding cost and timing.
A more successful development path adds more weight to distillation testing, specifically in the early design evaluation phase, but air/water hydraulic tests are not entirely abandoned. Consequently, the later valve designs, currently known as the Sulzer UFM valve, were mainly performed in Sulzer's 1000mm distillation column and external distillation columns of industrial size.

1. Introduction

In the long history of distillation tray research, the majority of public and industrial studies relied on air/water testing. The reasons are obvious: simplicity, safety and cost considerations.
Also in recent publications on tray research, air/water is still omnipresent as a test system. Van Sinderen et al. (2003) used an air/water test facility to investigate bubble formation and entrainment of sieve trays. The investigation by Moses et al. (2014) dealt with a similar topic as the present study and focused on the influence of the system properties on entrainment and weeping. Zhang et al. (2017) used a 1.22m air/water simulator especially to validate computational fluid dynamics simulation of the simulator geometry. One of the ever-ongoing questions in the research of column internals is therefore how air/water experiments translate to real life systems and how to predict useful capacity. This question is of particular importance for industrial research aiming at developing reliable products that serve the end user. As a new column internal is developed, a sequence of tests is required to progress from a concept to a final product. The main steps are depicted in Figure 1.

Figure 1: Typical steps for product development of new column internals

At the beginning, small-scale experiments allow fast changes of the geometry and can give a first idea of how a concept performs. In the next step, the design is taken to a larger scale to eliminate typical inaccuracies of small-scale setups such as wall effects. If the results still look promising in the larger scale, the design can be taken to a pilot plant to evaluate the distillation performance. If the performance meets the expectations at this stage, the product development is a success.
Sometimes, there is also the opportunity to test the product in an independent facility at even larger scale and with yet another test system. A suitable place to conduct such tests is the well-established and recognized test facilities from Fractionation Research Inc. in Stillwater/USA.
The number of experiments decreases with the facility complexity mainly due to costs. Therefore, if possible, one would want to achieve a useful amount of design variations in the early phase based on air/water.
The present paper contains examples of a real valve development project where the limits of air/water testing appeared at a late stage in the project. They were collected during the development of the Sulzer UFM valve, which is shown in Figure 2. Other aspects of this research project had already been considered by Hirsch and Pilling (2010).

Figure 2: Tray with Sulzer UFM™ high performance valve

1.1 System properties of water vs. standard distillation systems

The deviation of system properties of the air/water system from the majority of commercial applications involving organic systems, poses the largest challenge in the interpretation of results from air/water testing. Table 1 shows a comparison of the properties of common test systems. The first differences are the densities. Air/water has quite a large density difference and ratio compared to the distillation systems. Further, especially the surface tension of water is much higher than for the other systems. In addition, the viscosity of water is relatively high compared to the organic systems at boiling conditions. Especially these two last parameters considerably influence the flow regime and the droplet breakup behavior on the tray. The properties of air/water are therefore not fully representative when it comes to the hydraulic characterization of trays.
Another challenge of classical air/water hydraulic testing is the absence of mass transfer information.

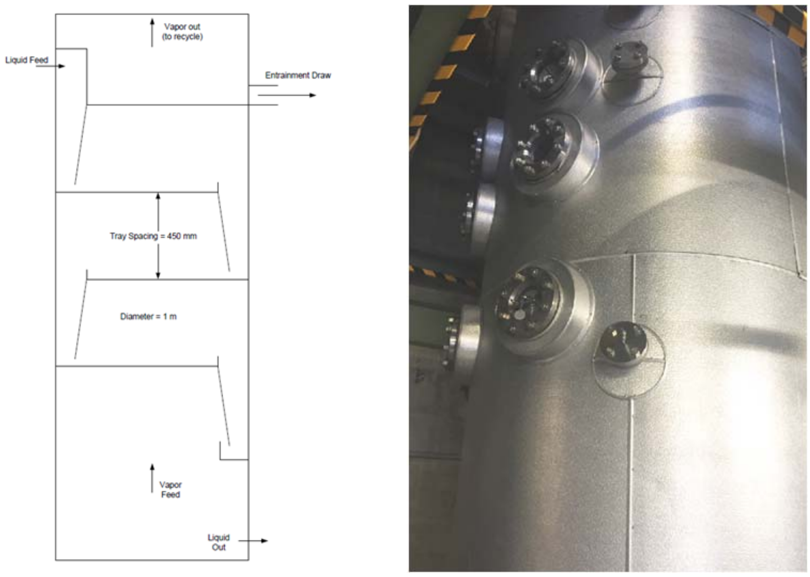
Table 1: Fluid properties of air/water at ambient temperature and test systems at boiling point (Onken et al. 1990). Exact values vary with composition.

	Air/water	Chlorobenzene/ Ethylbenzene	Cyclohexane/ n-Heptane
Pressure, bara	0.96	0.96	1.62
Gas density, kg/m^3	1.1	~3.3	~5.2
Liquid density, kg/m^3	998	~830	~650
Surface Tension, mN/m	72	~18	~14
Viscosity, cP	1	~0.3	~0.25

2. Test Setup

2.1 Facilities

The air/water test column used by Sulzer consists of a 1000mm diameter test section equipped three trays. The top of the column is equipped with a mist eliminator and an entrainment draw-off tray. The liquid is fed into a dummy downcomer and is recirculated with a pump. The gas is circulating in a closed loop using a blower. (Figure 3a)



(a) (b)

Figure 3: (a) Sketch of the air/water test column (b) picture of the 1000mm ID distillation column

The distillation column used in this study (Figure 3b) is a 1000mm diameter column operated with Chlorobenzene/Ethylbenzene. The column is operated at total reflux and samples are taken at each downcomer outlet.
It is common practice to use the gas load factor based on column area to characterize the gas flow:

$$C_s = u_s \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad (1)$$

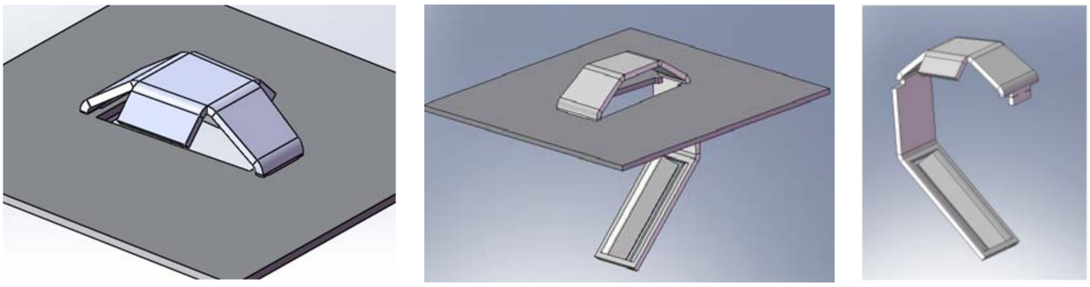
With u_s being the superficial velocity in the column, the gas and liquid density ρ_g and ρ_l respectively.
The liquid loading of a distillation tray is usually characterized by the weir load:

$$WL = \frac{Q_l}{L_{Weir}} \quad (2)$$

With the liquid rate Q_l and the weir length L_{Weir}

2.2 Valve prototype designs

In the course of the valve development project, many different valve designs had been tested. The intention was to modify the base shape of a Sulzer MVG™ valve and understand the impact of this change on performance. One of the tested prototypes was the so-called “Cross Valve” (Figure 4a). The name was chosen since it looks like a cross when looked at it from the top. The target was to redirect the gas flow out of the valve to achieve a better aeration between two valves and therefore increase the mass transfer and the capacity.
A second idea was the addition of a simple device below the tray deck to coalesce and deentrain liquid entrained from the froth of the deck below. After a series of small scale air/water tests, the design in Figure 4b was selected as the most promising one. It was called C-Valve due to its C-shape when looking from the side.
The third design is a combination of the Cross Valve and the C-Valve (Figure 4c) and was meant to combine the advantages of the valve shape and the deentrainment mechanism.



(a) (b) (c)

Figure 4: Unreleased research prototypes: (a) “Cross valve”, (b) “C-Valve” (c) “Cross C-Valve”

Sulzer also performed CFD (computational fluid dynamics) studies of the Cross Valve in a gas phase only flow simulation to see the impact of the added flaps. As can be seen in Figure 5, the added flaps indeed dramatically change the outflow behavior of the standard Sulzer MVG valve and redirect the flow to the tray floor. This was intended to make better use of the area between two valves and therefore achieve a more homogenous aeration of the liquid.

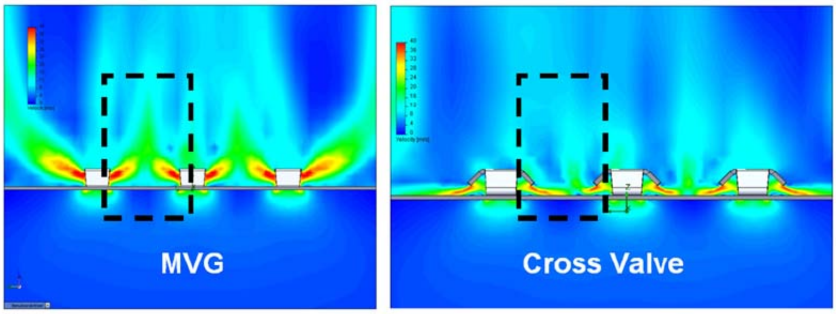


Figure 5: Gas phase flow simulation of the Sulzer MVG™ valve compared to the Cross Valve showing the downward flow due to the flaps.

2.3 Tray Design

The tray was a 1-pass tray equipped with a conventional downcomer. The same downcomer was used for all tests. The valve pattern on the tray panels was adjusted to accommodate the different valve types. The open area was adjusted to reach a similar pressure drop. The outlet weir height was kept constant at 50mm.

3. Results

3.1 Results of valve prototype designs

The valve prototypes shown in section 2.2 were first tested in the air/water test column. The results (Figure 6) show a very successful outcome. The addition of the flaps indeed increased the capacity based on 10% entrainment by about 4-8%. In addition, visual observation in the simulator confirmed a substantial change of the froth behavior. It appeared that the valves produced a much stronger downstream push, which can probably be attributed to the openings beside the flaps.
The second test with the C-Valve was another success. The performance also increased by around 4%.
Finally, the two modifications were merged with the expectation to achieve a cumulative capacity enhancement. As anticipated, the overall tray capacity could be improved by almost 10% in the air/water test column. Based on the success of the air/water tests, the trays were tested in the distillation column in Chlorobenzene/Ethylbenzene at 960mbara and total reflux. The results (Figure 7) gave a completely different picture. The Cross Valve show a substantially lower efficiency and therefore lower useful capacity than the Sulzer MVG tray. Even the turndown appeared to be reduced.
The result of the C-Valve showed, that the deentrainment device had only a marginal effect on capacity and thus could not deliver the improvement, which was found in air/water.
The former successful addition of the deentrainment device to the Cross Valve (Cross C-Valve) could not recover the low performance of the Cross Valve. The average efficiency of the Cross C-Valve can be

considered similarly low as the Cross-Valve. There is a small gain in efficiency at around 0.09m/s due to the device, which, considering the result from the C-Valve, is not significant.
This leaves the standard Sulzer MVG valve as the most successful design in this direct comparison.

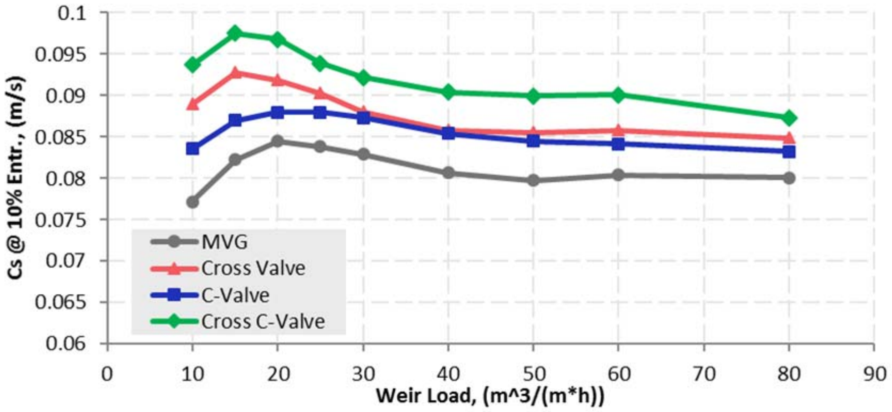


Figure 6: Air/water results for the different valve modifications

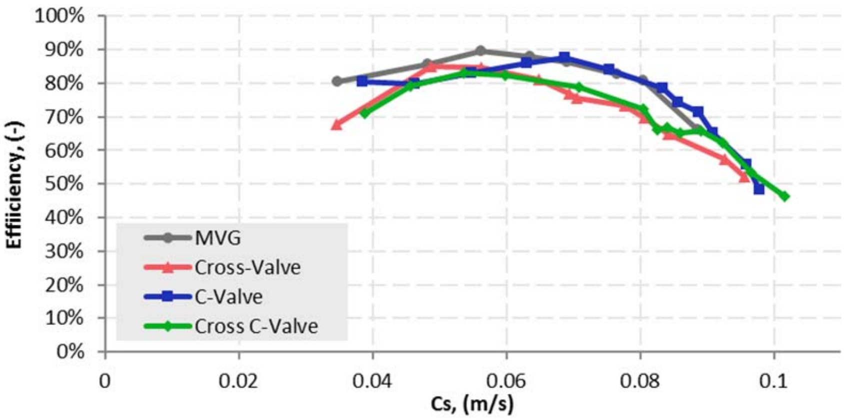


Figure 7: Chlorobenzene/Ethylbenzene result for the different valve modifications

3.2 Discussion

The experimental study shows how a design, which looked promising in air/water, had to be eliminated because it could not meet the expectations in a test with Chlorobenzene/Ethylbenzene. The main reason is the lower average efficiency of the Cross Valve compared to the reference Sulzer MVG valve. It seems that the high apparent hydraulic capacity in the simulator was achieved by a flow pattern change. This increased the capacity in the simulator, but it did not improve the capacity in the distillation test. The flow pattern was even counterproductive for the mass transfer. The reason for this behavior can probably be found in the opening between the flap and the valve top. This opening created a strong push and a significantly different outflow pattern and caused a negative influence on the mass transfer.
The addition of the deentrainment concept, which showed promising results in air/water, did not exhibit the same benefit in the distillation system. The different system properties changed the results. The high surface tension of air/water allowed a much better coalescence and therefore a higher capacity gain in the simulator. In the lower surface tension system, this mechanism was less effective and thus could not deliver the expected results.

3.3 Alternative Development Paths

The given example showed that valve tests in air/water could mislead the development path. In the most recent development, the new Sulzer UFM AF, mostly distillation tests were used to rule out wrong decisions in the design phase. The Sulzer UFM AF is in fact a larger version of the standard UFM valve, but contrary to the

UFM, it is a fixed valve suitable for potentially fouling processes. The development of this valve in fact required several distillation tests to assure a design, which delivers the expected performance and robustness. Air/water testing played still a small part of the development, but it was mainly used for pressure drop measurements and correlation development.

4. Conclusions

Air/water testing has always played and will continue to play an important role in column internals development. Air/water tests are able to produce results in the correct magnitude which can be used for correlation development, where knowledge of the influence of the fluid properties is mandatory.
On the other hand, the unusual fluid properties of air/water and the missing mass transfer information are a handicap. Fluid dynamics and regimes, which can be created or influenced in air/water, might behave differently in another test system or in the real distillation service. In the present case, several promising valve designs were developed in the air/water test system, but they had to be ruled out when the designs were tested with Chlorobenzene/Ethylbenzene.
In modern high capacity valve tray development, testing should therefore focus on a real distillation system in a sufficiently large scale. Even though it sounds counter-intuitive, this path can save costs at the end because under-performing designs can be identified more reliably and already in an early phase of the project.
To raise the impact of hydraulic testing we recommend switching to a system with an organic liquid, e.g. iso-paraffin. Measuring the residence time distribution using a stimulus-response method may provide an interesting basis to predict efficiency in an early development phase. Another approach may consist in combining the hydraulic test with an integrated absorption experiment to learn how mass transfer is affected by design modifications.

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