Recent Developments in Separation Equipment for Very Large Distillation and Absorption Towers

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Abstract. The need for distillation and absorption columns with diameters above 10 meters has been rising in the last 10 years. Economies of scale lead to single production lines for very large ethylene, aromatics and propane dehydrogenation plants requiring column diameters as large as 16 meters.

The requirement of SO2 and CO2 capture from power plants has led to even larger, sometimes rectangular, tower designs to process the huge quantities of flue gas emitted. Today, demo sized plants already have equivalent diameters beyond 16 meters.

This paper will discuss learnings from the design and operation of these exceptionally large towers in the different industries mentioned. Several real problems which could arise due to the large diameter and their solution will be shown. The paper will give an overview of dedicated tower internals which can optimize the size of the towers as well as the operating parameters.

Keywords Mega, World Class, Diameter, Carbon Capture

Introduction

In the latter half of the 20th century, very large plants were commonly constructed with duplicate trains. This is a conservative method, but consumes more materials, plot space, and CAPEX when compared with a single mega sized process unit. "Mega" generally refers to any dimension that is large enough to require distinctive design, construction, installation, and operating requirements. For this paper, mega columns are generally over 10 m in diameter and/or over 80 m tall. Over the last few decades, columns as large as 16 meters are now found in new ethylene, aromatics, and propane dehydrogenation plants. The global drive for SO2 and CO2 capture from power plants has led to even larger, sometimes rectangular, tower designs to process the huge quantities of flue gas emitted. These mega columns are at the forefront of mass transfer technology and will play a critical role in carbon capture on a massive scale.

Very large diameters

Column diameter is directly related to capacity. The more product processed in a column, the larger the diameter will need to be, assuming the column internals remain the same type. Note that moving from standard to high performance internals will allow the designer to reduce the necessary column diameter. Very large diameters are the function of a few different variables, typically found occurring simultaneously in the same process.

- Low vapor density: Low pressures, such as vacuum pressures, reduce the vapor density and therefore create substantially higher volumetric flow rates. Column hydraulics are based predominantly on volumetric flows, not mass flows. Note that column feed nozzles do depend on momentum, so mass and volume flows are both considered in a proper design.
- High plant feed rates: Mega sized columns are often found in exceptionally large world-class operating facilities. Economies of scale drive plants to be larger and larger. Globalization now makes it feasible to build massive plants that import copious amounts of feed from various sources and process and ship products out to a wide array of customers. High feed rates mean larger diameter columns.
- High internal reflux rates: When a column has a difficult separation, requiring a very high number of theoretical stages, this is usually also accompanied by a very high reflux ratio. This creates a lot of hydraulic

traffic in the column with very large amounts of vapor going up and interacting counter-currently with very large amounts of liquid traveling down the column. These substantial volumes of vapor and liquid require a proportionally larger column cross-sectional area, leading to large diameters.

Very tall heights

While column diameter is mainly a function of capacity, column height is mainly a function of separation difficulty, product purity specifications, or theoretical stages required. Common examples of this are the superfractionators for olefins, such as ethane-ethylene and propane-propylene splitters (C2 and C3 splitters). There are very many of these columns requiring over 100 theoretical stages. They are often over 70 m tall, and they have been around for many decades. These tall columns do require some special considerations but are really nothing new. Some facilities have chosen to break the column separation process into two discrete physical columns with one column serving as the bottom, stripping section of the process and the other column represents the top, rectification section of the process.

Another process application requiring extreme column height is isotope separation. One of Sulzer's first column applications was for the separation of deuterium from water. This was accomplished using very high efficiency Sulzer BX™ or CY™ gauze packings to minimize the overall column height required. As time has passed, even more extreme applications have emerged. There are now columns requiring thousands of theoretical stages to separate isotopes. An example of this is the Aria Darkside project which separates Ar39 from Ar40. The purified Ar40 is then used in an effort to detect dark matter in the form of weakly interacting massive particles (WIMPs). This incredibly difficult separation requires approximately 3,000 theoretical stages. This is around 100 times higher than a typical distillation application. The column has 112 beds of Sulzer CY gauze packing and the total column height is an astounding 350 m (taller than the Eiffel Tower). The column diameter is quite small at around 200 mm, including a cold box jacket, and it therefore does not have the mechanical stability to stand without external support. Because of this, the column has been submerged into an existing mineshaft in Sardinia and is hung rather than self-supporting from the base.

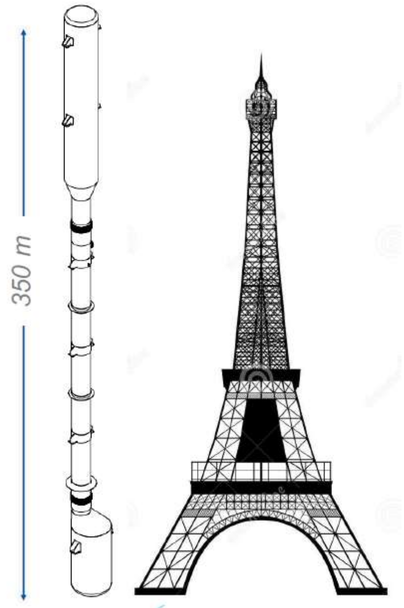

Fig. 1 A Very Tall tower for separation of Ar39 from Ar40 [1]

General design considerations

Mega columns require large fluid flows that travel large distances. Excessive fluid momentum creates concerns with maldistribution within the column that can adversely affect both capacity and efficiency. Feeds will need to be carefully designed.

In many cases, feeds enter a column using multiple nozzles at the same elevation. Interaction between the flows of these nozzles must be well understood to ensure proper distribution to the column internals. Results from a representative CFD (Computational Fluid Dynamics) study are shown below in Figure 2.

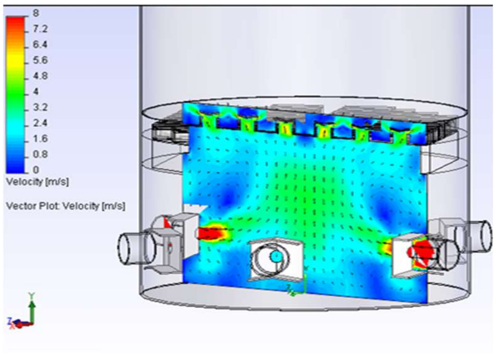

Fig. 2 CFD Study of multiple feed hydraulics

In packed columns, an exceptionally large diameter does not present too many difficulties for the packing itself. It replicates itself nicely across every diameter. With trayed columns, large diameters will require larger liquid flow rates that need to disperse laterally on each tray. This will be done using 4, 6, or even 8 pass trays, or a high-performance multi-pass tray like a Shell HiFi™ Plus tray to proportion liquid flows into more manageable internal streams.

Importance of liquid mixing at the feed stage

One particularly critical aspect in very large towers is the distribution of the feed liquid and the liquid from the fractionation section to the stripping section. The feed location for a well-designed distillation tower will be optimized to give the lowest possible reflux rate for the given number of theoretical stages. In practice, this means that at design conditions with an optimized feed stage, the composition of the liquid coming from the fractionation section will be roughly the same as the feed liquid. In this situation mixing the two liquid flows is not that important as their compositions are similar. However, many towers will be operating at other than design feed compositions for most of the time. This can for example be because the design feed composition is an average to be expected between start and end of run conditions for a reactor further upstream of the tower. It can also be more unexpected e.g., because a tower further upstream is functioning better or worse than designed.

If the actual feed composition is different from the design, the given feed stage will in general not be at the optimum location anymore. The feed coming from the fractionation section will probably still be close to design, but the composition of the feed liquid will be significantly different. To have a well-functioning stripping section, mixing these two liquid streams has now become especially important.

One configuration for a mixing box re-distribution for packing is shown below in Figure 3. Rather than feeding directly onto the top tray or in the distributor of the stripping section as is done in smaller towers, the feed is fed in a collector below the fractionation section and is then properly mixed in a central mixing drum or on a collector-distributor tray.

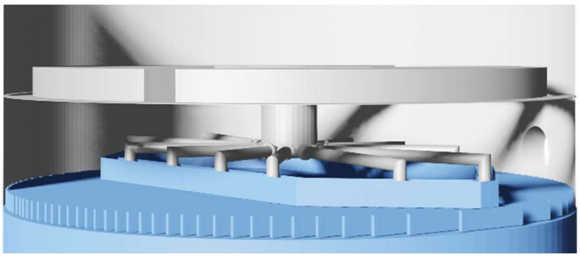

Fig. 3 Mixing box feed into packing pre-distribution channel

For smaller columns, multiple feed stages are often used to cope with different feed compositions. For mega columns this is in most cases too costly. Multiple feed locations not only raise the investment costs for additional inlet devices, nozzles, piping, valves, and associated installation work, but would also require a significant amount of additional tower height to accommodate the different feed sections.

Once the liquid is properly mixed it should also be distributed equally on the packed beds or tray decks. If possible, costly beams which could also interfere with the distribution system should be avoided. For columns with structured packing, Sulzer has more than 50 years of experience with distributors supported by the packed beds with integrated leveling devices which do not need additional beams. For the best possible distribution, inlet-pipe systems should have a symmetrical arrangement and the flow should be split equally from inlet nozzle into the distributor to limit flow-impact in the channels and avoid splashing and vibration.

Vapor distribution and reboiler draws

Another design aspect which must be considered with special attention because of the huge column size is vapor distribution. It is of particular importance if the tower has multiple reboiler liquid draw-off and return nozzles [2]. Multiple smaller draw-off nozzles will save column height but will pose equalization issues. Figure 4 below shows a collector-vapor distribution configuration which distributes vapor and collects the liquid for 4 reboilers. The device ensures that equal flow is maintained to the remaining three reboilers when one of the reboilers is not in service.

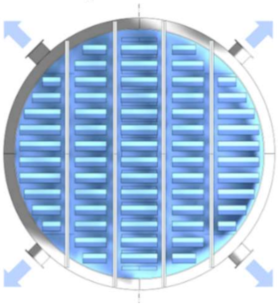

Fig. 4 Liquid Collector, vapor distributor and draw-off for 4 reboilers

An additional challenge arises for vapor distribution when the mega columns must be designed for the lowest possible pressure drop as e.g., absorbers in post-combustion CO2 capture plants. An example of such a design using CFD was shown in Fig. 2. This topic is discussed in [1].

Product specifications and column control

Mega columns require special consideration when defining the process specifications and the associated control philosophy. The effect of changes of mass balance control parameters like boil-up, reflux or product flow will be slower in very tall columns due to the proportionally higher residence time of fluids in the column (e.g., 120 trays will have four times the residence time of 30 trays). Strong variations in feed composition should be avoided or at least predicted with feed forward control methods. If very low impurity levels of 10-100 ppm are required for both top and bottom products, it can occur that due to an unsuitable or untuned control system, impurity compositions swing from far better specification for the top product and worse than specified for the bottom product to the opposite situation. In [3], Henry Kister gives an excellent overview of the pros and cons of different mass balance control philosophies dependent on process design parameters which can also be used for mega columns. Even if the right philosophy has been chosen, a greater than usual design reserve and more sophisticated feed forward control or more flexible product specification ranges might be required to get stable operation.

Mechanical considerations

With large diameter columns, out of roundness can be a significant issue. The ASME (American Society of Mechanical Engineers) standard for allowable out of roundness is +/- 1% of the tower diameter. Larger columns mean larger tolerances. Support rings and beam seats need to be wide enough to cover this tolerance. As an example, a column with an ID of 12 m would require a minimum support rings width of 120 mm and a minimal overlap of the tray deck of 60 mm (i.e., half a ring width).

Support rings historically had tolerances of +/- 3 mm. This is a burdensome requirement for vessel fabricators constructing very large towers. A reasonable approach is to define a maximum degree of tilt that can provide a practical degree of allowable levelness. Figure 5 shows an example of two criteria which can be used by both fabricators and inspectors. The criteria should suffice for both trayed and packed towers, regardless of diameter. Note that the stair step pattern at lower diameters is a function of the 1/8" or 3 mm increments.

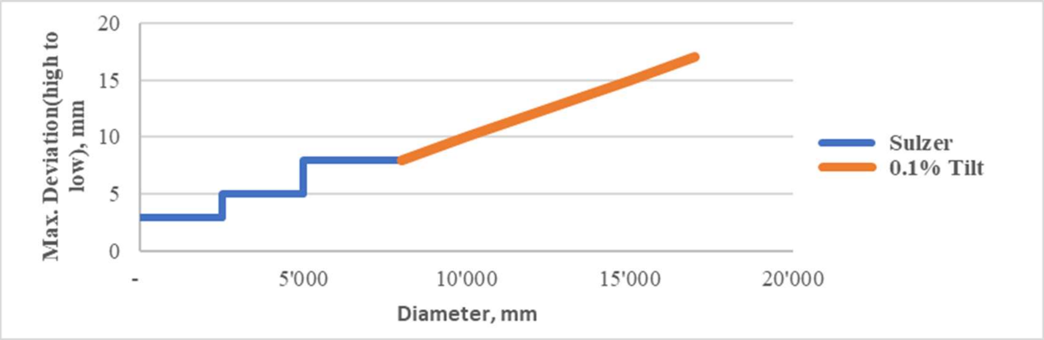

Fig. 5 Support ring levelness criteria

The biggest concern regarding large diameter tray levelness is sagging in the middle portion. The possible effect seen for a column with ID of 11.6 m (as shown below) with deflection can be a loss of tray efficiency of 30%. The typical deflection criterion today is 1/900 of tower ID which is obtained by combination of proper beam configuration, panel span width optimization, and use of downcomer walls to provide mechanical strength.

To improve mechanical strength, thicker downcomer panels can be used whereas lattice truss beams can be used to tie two or more trays together in an economical manner. Care should be taken that beam seat size can accommodate the allowable out-of-roundness of the tower. Thermal expansion must also be accounted for. If tray or column internal materials differ from the tower material, calculations should be made to properly address thermal expansion (e.g., 304L has nearly double the thermal expansion compared to carbon steel).

Fig. 6 Lattice beams with proper beam seats and consideration for thermal expansion

Correct space between beds and trays

A costly design issue which often occurs in the early design stage of mega columns is that not enough space is foreseen for different inlet, draw-off, or distribution devices. Design rules for such sections are often based on maximum column diameters of 6-8 m. In early column design stages used to get costs from vessel vendors, the height specified between packed beds, at the feed or draw-off stages of both packed and trayed towers is often too small for columns with ID larger than 10 m.

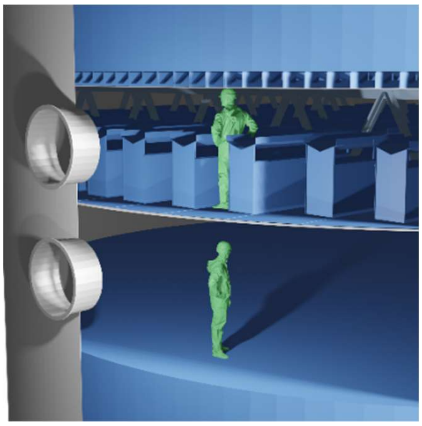

Fig. 7 Space requirements in mega towers

Additional height for these sections is required due to the increased liquid hold-up which must be collected, be given sufficient residence time for phase separation and which must be mixed. Figure 7 above gives an impression of internal sizes in a mega tower. It is recommended to increase heights for feed and re-distribution sections to at least 4 m and to also foresee larger than usual manholes to accommodate easier installation of larger than normal parts.

Conclusions

The number of mega columns in the world is steadily increasing. These columns have specific challenges due to:

- Relatively tight specifications on diameter, levelness, and thermal expansion
- Scale-up of trays and distributors to ensure uniform flow across the entire column cross section
- Residence time and process controls
- Mechanical design across such large distances
- Installation time, especially for revamps

These challenges have been successfully addressed with a growing list of mega column applications. The future is bright for mega columns and their growing and vital role throughout industry.

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