100 Years of Distillation with Trays and Packings and Beyond

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Abstract. This paper covers the topics of trays and random packings through history with a focus on the past 100 years. It is obvious that both trays and packings have been in existence for more than 100 years. The author's intent is to bring the reader up to date with respect to current design techniques and practice.

Keywords: Distillation, Random Packing, Trays, History, Packed Tower

Background

Distillation has been practiced for a long time [1] and 100 years is not a very long time in the history of distillation since this time line goes back to only just a few years after the first World War. Distillation was already being practiced quite extensively by the early 1920's. It was being used to basically refine diesel oil and gasoline, and to also make ethanol, vinegar, essential oils and to refine various chemicals [2]. It is very important to note that temperature indicators such as thermometers and thermocouples (~1902) [3] have already been invented and are being used extensively. As we all know, without accurate temperature measurements, distillation would simply not function. Chemical Engineering was still in its infancy and before 1922 no simplistic distillation stage calculation method had been invented yet. With the development of the McCabe-Thiele (1925) [4] and Ponchon-Savarit (1922) [5] [6] methods, distillation technology with stage calculations became widely accepted. By the time the first edition of Perry's Chemical Engineering Handbook was published in 1934 [7], the understanding of vapor-liquid equilibrium was well understood for numerous compounds. An excellent work with regards to the history of Distillation was written by James Fair in 1983 [2].

Packings

The optimum design of a random packing for heat and mass transfer columns must take into account the following basic balance conditions, Fourier's law for heat transfer, Fick's law for mass transfer and Newton's law for impulse transfer, as well as the thermodynamic condition of the phases involved. As the history of random packings was always linked to the fundamental understanding of these interactive conditions, the article will start with a short history of modelling thermodynamics, fluid dynamics and heat/mass transfer. For a thorough history (and future) of structured packings, please reference the 2002 paper by Spiegel and Meier [8]

History of thermodynamics

The baseline for thermodynamics has always incorporated temperature and pressure as reference for experimental conditions. Galileo Galilei invented the thermoscope in 1592, and Evangelista Torricelli invented the barometer in 1643, through which Fahrenheit developed the first temperature scale in 1714. The principle description of thermodynamics started in the 17th century and has been under continuous development since. Since the 19th and 20th centuries, modeling thermodynamics has become theoretical in detail, but the theories have been increasingly difficult to follow without a computer program. In 1941, Konrad Zuse, together with Helmut Schreyer, launched the first digital computer. In 1954, the first mass-produced computer model, the IBM 704, came on the market, and in 1981, IBM introduced the first personal computer (PC). In the 1960's the first companies started to apply computer programs to predict mass and heat balances, physical properties and equilibrium data. With the availability of cost-effective PCs, numerous scientific groups at universities have started to develop extensive thermodynamic models. In general, one can state that the accuracy of thermodynamic modeling of physical properties as well as phase equilibria is currently outstanding. The accuracy of the description for thermodynamic properties is noticeably better than that for heat, mass or impulse transfer in a mass transfer tower. This discrepancy is not because of the longer history of thermodynamic research but the more complex interaction between the fluid dynamics and heat and mass transfer in packed towers.

History of impulse, heat and mass transfer in packed towers

Thomas Graham first published experimental investigations regarding gas diffusion processes in 1832, although he was not able to present a prediction model [9]. Almost 100 years later, in 1934, Gilliland provided the first equation to predict gas side diffusion coefficients, which was proven only by a limited amount of experimental data [10] [11]. In 1966, Fuller, Schettler and Giddings published the first reliable equation for the prediction of gas side diffusion coefficients at low pressures and moderate temperatures [12]. Sherwood, Pigford and Wilke modified the equation in 1975 based on experimental binary diffusion data for elevated temperatures [13]. The liquid side diffusion process was noticeably more difficult to study experimentally, as the diffusion process in liquid is much slower than in the gas phase. Although the initial approach was published by Arnold in 1930 [14], the first experimentally reliable equation was published by Wilke and Chang in 1955 [15].
The reliable prediction of diffusion coefficients is essential for the proper estimation of heat and mass transfer processes. The first historical approach for predicting transfer coefficients was related to heat transfer, as temperature could be reliably measured since the invention of the thermometer and the temperature scale.
A fundamental investigation of molecular diffusion between gas and liquid phases was published by Fick in 1855 [16], when this researcher proposed an analogy to heat conduction, as introduced by Fourier in 1822 [17]. The first general description of diffusion processes between phases was published by Maxwell in 1866 [18], but the first dimensionless approach for heat and mass transfer coefficients in wetted-wall columns was published by Chilton and Colburn in 1934 [19].
Additionally, in 1925, the approach of McCabe and Thiele [4] was essential for the graphical description of concentration profiles along the column for which Colburn expressed a relationship to predict the number of theoretical stages in 1939 [20] after publishing the HTU-NTU concept in 1935 [21]. Krishnamurthy and Taylor in 1985 [22], Andrzej Górak in 1983 and 1987 [23] and Taylor and Krishna in 1993 [24] published an extensive mathematical model for multicomponent mass transfer processes in packed columns.
The first well-accepted concept for the prediction of the gas- and liquid-side mass transfer coefficients in packed towers and for the modeling of the effective packing surface areas was published by Onda et al. in several papers from 1958 to 1968 [25]. Although these equations were only based on a limited number of test systems and early-generation random packings, Onda's equations have been widely used for mass transfer column designs. Additional valuable equations for the prediction of mass transfer coefficients and the effective packing surface area have been published by Shulmann et al. (1952), Mersmann et al. (1978, 1985, 1986) and Bravo and Fair (1982) [26]. Schultes present the most recent approach in a paper in 2018 that refers to the Billet and Schultes model in 1999 for the prediction of volumetric mass transfer coefficients in combination with the Tsai model from 2010 for the effective packing surface area [27].

The above description shows that a proper prediction of thermodynamic and fluid dynamic parameters, especially diffusion coefficients and mass transfer coefficients, was only given from the 1950s onward. As these parameters are key factors for the optimization of mass transfer towers, more efficient random packings were also developed from 1950s onward.

Random packing history and design principles

Random packings have been used in process industries for decades. The original random packings in the 18th century consisted of shards, stones, and balls, either from glass, coke or ceramics (Fig. 1). As these packings offered only their outer surface for the contact between gas and liquid, the mass transfer area was limited and so was their efficiency. In addition, the pressure drop was high, and the flow rates through the columns were limited. Due to the size variation in the packings inside a column, it has been difficult to predict performance, and a noticeable overdesign of the towers has been required to achieve a desired separation under industrial conditions.

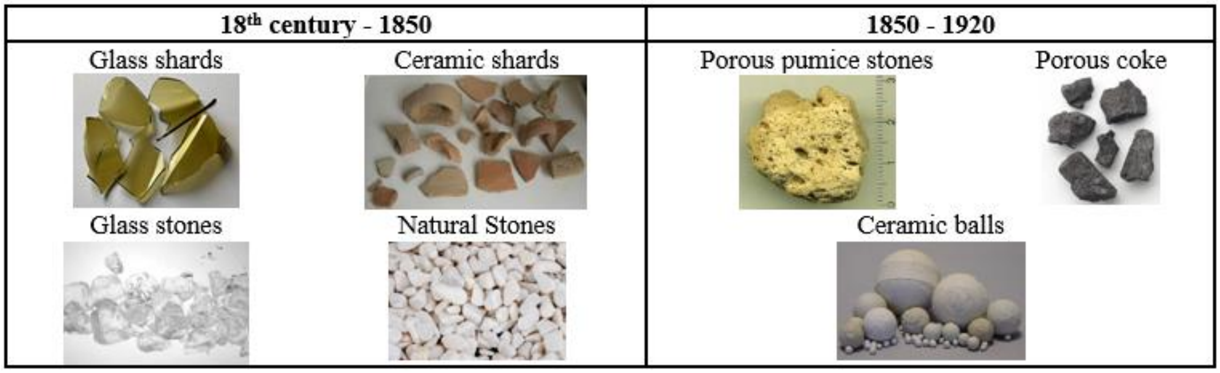

Fig. 1: Tower packings used/introduced between 18th century and 1920

First-generation random packings

Dr. Fritz Raschig, a chemist from Ludwigshafen/Germany, established a new chemical plant in 1891 focusing on the separation of phenols (carbolic acid) from cresols by batch distillation. As the volatility between phenol and cresol is relatively low, it is a very time- and energy-consuming process.

To improve the yield and capacity of the distillation process, Fritz Raschig chose to operate a single continuous distillation column. Instead of using glass and ceramic shards, this researcher filled the distillation column first with wine bottlenecks for a more open and geometrically more regular packing arrangement (Fig. 2.). However, Raschig experienced that glass necks break into shards during the heating and shutting down of the distillation process which is why he used open tailor's finger thimbles in a second trial. The packing stainability improved, but a homogeneous and repeatable packing arrangement could not be generated, as the thimbles were slipping into each other. Last, a metal pipe was cut into pieces with the length being the same as the diameter. By this procedure, a homogeneous, reproducible packing arrangement was generated in a single tall vacuum distillation column with limited pressure drop. The high purity and yield of phenol and cresol were remarkable, resulting in a significant marketing advantage. This technology was protected for more than 15 years, but due to competition, in 1914, a patent was registered. It took a very long time to process the patent, but finally, in 1920, the patent was granted. In 1914, Raschig called his product "Raschig's Ringe" (engl. Raschig's Rings), which was the first homogeneous and reproducible random packing arrangement on the market. Later, the name "Raschig®-Ring" became the synonym for random packings on the market. Until 1944, Raschig-Rings were the only hollow shaped random packing on the market. In 1921, Raschig started to produce Raschig-Rings in his own ceramic factory in Ludwigshafen and supplied the product to the market.

Fig. 2: Development of "Raschig's Ringe" via glass bottlenecks and open tailor finger thimbles.

The next fundamental invention was given by Professor Ernst Berl. Ernst Berl was originally a Chemistry Professor at the Technical University of Vienna/Austria but moved to Germany in 1919 as a Professor to the University of Darmstadt. In Darmstadt, he invented the so-called ceramic Berl-Saddle and received a patent in 1931. For many years, this Berl-Saddle was a strong competitor for Raschig-Rings, as it provided a lower pressure drop and increased throughput capacity, see (Fig. 3).

Second-generation random packings

In the 1940s, Dr. Wilhelm Pfannmüller worked for BASF in Ludwigshafen with the intention to upgrade a distillation column operating under vacuum. A metal random packing with lower pressure drop than Raschig-Rings was needed. By intention, the cylindrical shape of Raschig-Rings was opened in a way that windows were intruded into the wall and pressed toward the packing center. By this technique, the packing surface area and consequently the column cross-sectional area were opened. The patent was launched in 1944. Compared with the Raschig-Rings, this invention showed both a lower pressure drop and increased capacity. Since 1944, this became known as the Pall® Ring and was the first 2nd-generation random packing product. Subsequently, other circular metal random packings came into the market with less material thickness than for Pall® Rings. Samples are shown in Fig. 3 as Ralu®-Ring and Hy-Pak® packings.

For ceramic material, Max Leva invented a new saddle-shaped packing, which was easier to produce than Berl-Saddles. This shape was named the Intalox® Saddle and was licensed to US-Stoneware (later Norton Company and Saint-Gobain NorPro).

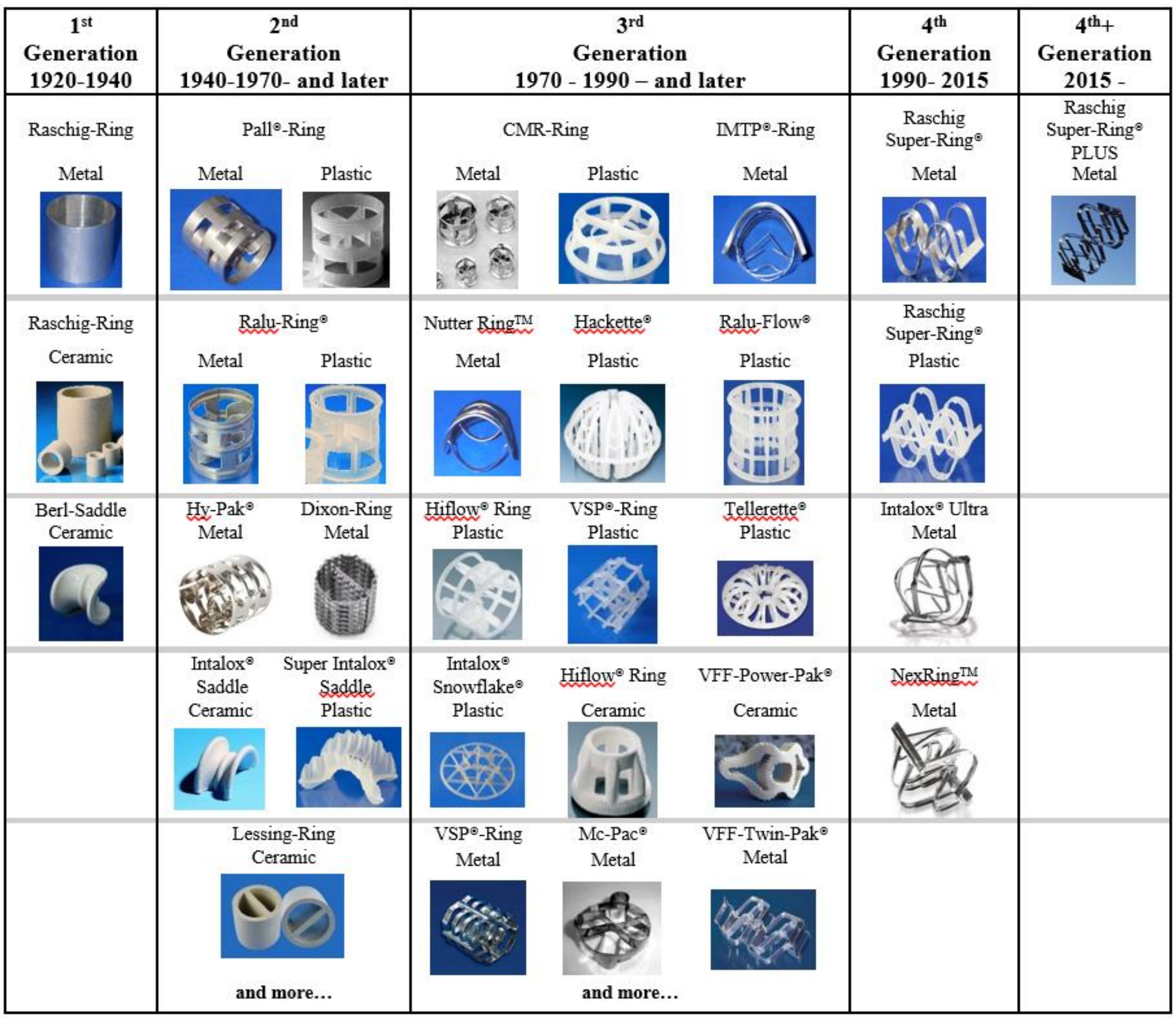

Fig. 3: Developments of metal random packings

Third-generation random packings

In 1971, Mass Transfer Co. in UK patented a product by reducing the height of Pall®-Rings to one third. The so-called Cascade Mini-Ring® (CMR™-Ring) provided a more horizontal orientation inside the tower than Pall®-Rings, opening up the column cross-sectional area to realize lower pressure drop and increased capacity. The CMR™ packings are currently called the first 3rd-generation random packing. Other inventors started to design packing pieces (not cylindrically shaped) by pressing metal strips out of a metal surface, such as IMTP® Ring in 1977 or Nutter Ring™ in 1984. In ceramics, the Hiflow® Ring was invented in 1982, offering a more open structure than the Berl-Saddle or the Intalox® Saddle. Between 1970 and 1990, multiple other geometries came into the market, as partly shown in Fig. 3.

Polypropylene was invented by Guilio Natta from Milan Polytechnic in Italy in 1954, and mass production started in 1957. The first screw-type injection-molding machine for industrial-scale production was launched by James Watson Hendry in 1946, which is why it lasted until the 1960s, when the production of plastic random packings started. Injection-molding production of packings allows many different designs to be fabricated, which is why most plastic packings are of the 3rd generation. The cost advantage of plastic packing was significant compared to ceramic and metal packings. The most popular packings are Hacketten®, Snowflake®, Ralu-Flow®, Hiflow® Ring, Tellerette® and CMR™-Rings, to name only a few of them. Compared to the 2nd-generation random packings, 3rd-generation geometries are grid-type designs, which means that they are more open for the transit of gas and liquid. Consequently, these packings offer lower pressure drop and more throughput capacity than 2nd-generation packings.

Fourth-generation random packings

Fourth-generation random packings are characterized by an optimized material arrangement of individual packing pieces and allowing the packing pieces to slip into each other for a more homogeneous material distribution.

The first 4th-generation random packing was invented in 1995 under the name Raschig Super-Ring®. More recent 4th-generation packings were introduced into the market under the name Intalox® Ultra in 2007 and under the name NexRing™ in 2014. Compared to the 2nd- and 3rd-generation packings, these 4th-generation designs have an even more homogeneous and narrow grid-like structure, which again provides lower flow resistance to the gas flow. The lower pressure drop of the 4th-generation random packings resulted in larger capacities without a loss in efficiency when compared to 3rd-generation random packings.

Although the shapes of 4th-generation random packings are becoming increasingly close to each other, there are still principle design differences available, which results in performance variances in terms of capacity, pressure drop and efficiency. Some packings are designed to enhance droplet formation while other packings prefer film flow. Droplets offer a high surface area for mass and heat transfer, but at high capacities, droplets are entrained easily with the counter current gas flow. Liquid film flow, on the other hand, is more turbulent than the liquid motion inside the droplets, which can have advantages and guides some inventions toward film flow designs. Another advantage for liquid film flow is that films are more resistant against entrainment than droplets, especially if droplets are small in high-pressure applications.

Fourth+-generation random packings

The latest random packing development was invented in 2014 and launched in 2015, the Raschig Super-Ring® PLUS. The patent is for a design that orients the packing elements predominantly in the horizontal position, which further opens up the column cross-sectional area, as described above for metal CMR™ packing. Without losing efficiency, a capacity increase and pressure drop reduction was realized compared to 3rd- and 4th-generation random packings. The design of the metal strips for Raschig Super-Ring PLUS® is designed such that packing nesting as a result of “slip-in arrangement” is no longer relevant.

Designing modern random packings

As described above, the development of a new, modern random packing needs to consider a fundamental knowledge of fluid dynamics as well as heat- and mass-transfer aspects inside a mass transfer tower. There are design features supporting one aspect but not supporting the other. The list in Table 1 can be beneficial for achieving a conclusive approach.

Low pressure drop

The application of thin material increases the void fraction of a packing without changing the principle geometry. A high void fraction maximizes the open space for gas and liquid flow, which results in reduced effective velocities, reduced pressure drops and more capacity.
Additionally, the packing surface structure impacts the pressure drop, especially at wetting rates where the packing is not completely covered by liquid. A smooth or microscale packing surface without re-enforcement bends or crimps does provide a low pressure drop.

High capacity

A high void fraction is important to open up space for gas and liquid flow and consequently to increase the throughput capacity. However, for a given specific surface area, the void fraction can only be increased by reducing the material thickness. A low material thickness weakens the packing strength, which is why random packings have a minimum material thickness.
Another parameter to consider is the free horizontal cross-sectional area, which is further described with Fig. 4. Fig. 4 shows a randomly packed and a stacked version of 15 mm metal Pall® Rings. Although the specific surface area and void fraction are almost the same, the pressure drop and capacity are different. Due to the very open horizontal arrangement of stacked Pall® Rings, the pressure drop of the stacked version is noticeably less, and the capacity is high. However, care needs to be taken as the mass transfer efficiency of stacked Pall Rings is reduced.

Target	Mechanism	Parameter to look at	Principle From	to
Reduce pressure drop	Increase packing void fraction	Reduce packing material thickness		
Reduce pressure drop	Generate smooth packing surface	Flat or micro scale packing surface		
Increase capacity	Increase packing void fraction	Reduce packing material thickness		
Increase capacity	Increase open column cross section area	Packing geometry/ arrangement in column		
Increase mass transfer efficiency	Increase gas phase turbulence	Increase pressure drop		
Increase mass transfer efficiency	Increase liquid phase turbulence	Minimize flow path length between mixing pools		
Increase mass transfer efficiency	Increase effective/wetted surface area	Strip arrangement rather than flat surface area		
Increase mass transfer efficiency	Homogeneous packing geometry	Avoid irregularity in packing shape/minimize diffusion length		
Increase mass transfer efficiency	Generate thin liquid films	Increase effective/wetted surface area		
Increase mass transfer efficiency	Homogeneous liquid distribution	High quality of liquid distributor		
Increase mass transfer efficiency	Homogeneous gas distribution	High quality of gas distributor		
Long live time	Increase material resistance	Increase packing material thickness/apply high quality material grade		
Strong packing geometry	Increase packing strength	Packing texture/reinforcements		
Reduce cost	Reduce packing weight	Reduce packing material thickness		
Reduce cost	Easy and fast production	High speed production machines		

Tab. 1: Overview of parameters to aid the development of new random packings.

High mass transfer efficiency

Increasing mass transfer efficiency in a random packing can be realized by increasing the mass transfer coefficient and/or the effective surface area. A high mass transfer coefficient, for example, can be realized by an increase in flow turbulence. On the gas side, this can be ensured by multiple flow path redirections. Consequently, a flow through a packing with many directional changes enhances the gas side mass transfer coefficient but also increases the pressure drop.
On the liquid side, one needs to consider a high number of mixing pools. Any material junction in a random packing generates a turbulent mixing zone between the film surface and the film under layer. It is also advantageous to

provide small metal strips so that the liquid film can wet the strips from both sides. As more packing material is wetted by the film flow, less film thickness is given and the mass transfer coefficient is higher.
For an effective mass transfer between gas and liquid, it is important to reduce the diffusion distance, especially on the gas side. Therefore, the distance between the core of the gas flow and the liquid film should be minimized. An inhomogeneous material arrangement, as in Pall® Rings, will have a longer diffusion path length than in strip-type packings of the 4th and 4th+ generations. The latest packing elements also slip into each other in a dumped arrangement to minimize the diffusion length.

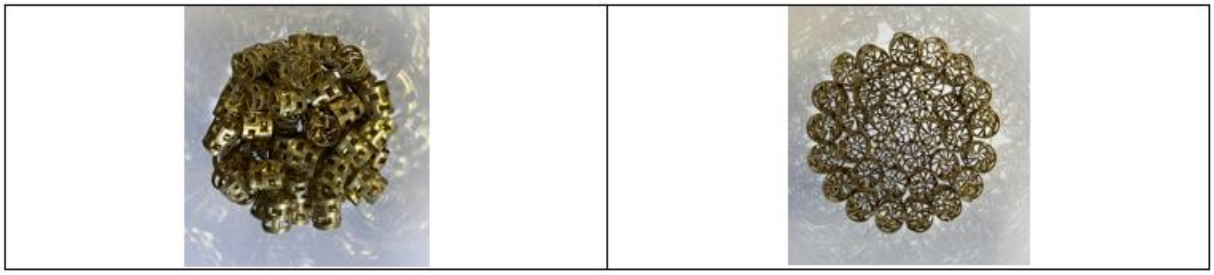

Fig. 4: Randomly dumped and stacked 15 mm metal Pall®-Ring

Strength of packing geometry

There is the tendency on the market to dump packings into tall beds, which minimizes the number of "non-mass transfer effective" redistribution column sections. However, as the beds become taller, there have been plenty of discussions about gas and liquid channeling due to inhomogeneous liquid flow across the column area [28]. Indeed, modern grid-type random packings have fewer liquid flow variations inside the bed than 1st- or 2nd-generation random packings. Consequently, modern 3rd- and especially 4th-generation random packings can be more properly packed to tall beds than 1st- and 2nd-generation random packings. As a result, modern random packings must be strong enough to withstand the increased packing weight of taller beds.

Low foaming tendency

The mechanism of foaming inside a packing is still a not well-understood topic. There are several physical properties, such as gas and liquid density, liquid surface tension and process parameters, such as gas and liquid velocities, that need to be considered to understand foaming conditions. In addition to these process parameters, the geometry of random packing itself can also support foaming. Some intensive experimental investigations in 2012 verified that random packings preferring film flow have a low foaming tendency [29].

Long life time of packing

Under corrosive conditions over time, the material thickness of a random packing often is reduced by chemical attack, even if high-quality materials are selected. The corrosion rate consequently determines the packing lifetime, which is why such processes start with packings having high material thicknesses. As described above, the choice of thicker packing material comes along with a higher pressure drop and lower packing capacity.

Packing cost

The most noticeable cost impact comes from the material weight (material thickness) and production time. Several vendors offer packings with very low material thicknesses, but as described above, there are limitations to thickness reduction. The other parameter to consider is the production time. High-speed automotive stamping and forming machines, with nearly no labor involvement, are essential for low-cost production. The cost of initiating and maintaining worldwide patents is also becoming significant and needs to be considered for most modern packing developments.

Design summary sample for Pall® Rings

Pall® Rings, for example, generate a high-turbulent gas flow by multiple directional changes, but they also come along with a high pressure drop and limited capacity. Although the high gas phase turbulence increases the gas side mass transfer coefficient, the majority of the Pall® Ring material remains at the circumference of the packing cylinder. Metal "fingers" direct a limited amount of liquid to the packing center, but there is no material available along the packing axis. Consequently, long diffusion distances between gas and liquid flow compensate for the positive mass transfer effect by the high-turbulent gas flow. Liquid dripping down from the metal fingers generates jet streams and can break up into droplets but ultimately falls into the liquid film below. This increases the turbulence in the liquid film but can generate foam as well. The Pall® Ring wall thickness needs to be high enough to withstand the weight of a packed bed, as the packing contact points for transiting the weight force are very limited.

Trays

A summary of Jim Fair's work [2] indicates that the majority of distillation tray applications in the 1920's were bubble cap type with some perforated plates (sieve trays) being used, for example, Air Separation. The economic depression of the 1930's followed by the second World War saw little new tray development. During World War II, extensive distillation improvements were made however to enhance war production of such things as fuels and synthetic rubber. Improvements however, were only made to existing technologies. During the war, bubble cap tray understanding improved greatly as well as sieve tray technology especially in the area of Latex production [30]. However, new developments in tray technology were not encouraged. It was not until the early 1950's that distillation developments rebounded with numerous new tray technologies emerging. This is when the movable valve tray, the Multiple Downcomer tray, the Calming Section™ Tray, the Ripple® Tray, the Slotted Sieve Tray and the fixed valve were invented. There then was a "second wave" of new tray development after the 1980s when the NYE tray [31], the SuperFrac® [32], the VGPlus™ [33], the ConSep™ [34], Triton™ [35], and the Ultra-Frac® [36] trays were developed and commercialized.
It must also be mentioned here that HiGee Technology [37] as well as Divided Wall technology [38] was invented in the 1930's but both were never really commercialized until the 1980's.

Union Carbide's Distillation Influence

When looking at the time period shortly after World War II, as stated above, this was the time of heightened tray technology development. One company that was performing extensive fundamental tray research in the 1950's was Union Carbide's Linde Division (UCC-Linde) in Tonawanda, NY. The Air Separations business was highly competitive at the time and anything that could reduce the pressure drop per theoretical stage to produce high purity oxygen was being examined carefully. Flow hydraulics on trays, hole size, weir height, downcomer sealing, and weir loading were all examined very carefully in the laboratories at UCC-Linde. The invention of the Slotted Sieve tray (push valves) came about in 1956 because tilting trays (to eliminate froth gradient) at small tray spacings was too challenging [39]. Lewis Case 2 [40] efficiency enhancement (Parallel Flow trays) enabled tray efficiencies to exceed 100% even when outlet weirs were eliminated entirely [41]. These fundamental studies enabled UCC-Linde to significantly reduce the cost of operating their Air Separation Units (ASU) by more than 20%. This worked so well that UCC-Linde decided in the mid 1960's to apply this technology to other industries (e.g., EB-Styrene, AA Grade Methanol and Olefins) [42]. Multiple Downcomer Tray Technology came about at UCC-Linde from the Direct Contact Aftercoolers in the ASU. These highly liquid loaded vessels had employed many downcomers to minimize weir loading and keep the pressure drop low [43]. Everything in an ASU was driven by the high discharge pressure of the Air Compressor and minimizing pressure drop was extremely important.
To maximize tray efficiency, UCC-Linde developed large diameter trays that used parallel flow to ensure that the liquid was flowing the same direction on every tray. This enabled a Lewis Case 2 efficiency improvement to the trays [40]. The tray was divided down the flow centerline with a baffle to keep the opposing flows from interfering with each other. The downcomer liquid was transferred from one tray to the next with chutes to get the liquid to the other side of the baffle. The tray deck was equipped with slots (push valves) to ensure the flow of liquid had perfect residence time distribution (RTD), eliminated froth gradient and maximized tray efficiency [44]. Figure 5, shows such a large diameter tray used in an ASU. Note that the diameter is approximately 10 feet (3 meters) and the tray spacing is about 8 inches (200mm).

Similar type trays were developed for the EB-Styrene industry where observed tray efficiencies were well in excess of 100% [45]. With the development of high capacity/low pressure drop structured packings with superior liquid distributor technology, these trays are no longer appreciated in the Air Separation industry as well as in EB-Styrene applications. However, renewed interest in maximizing tray efficiency in conventional distillation applications has enabled push valve technology to be applied to modern-day high-performance trays (e.g., VGPlus and SuperFrac

trays). FRI (Fractionation Research Inc.) has recently completed a preliminary study of efficiency enhancing push valve devices on fixed valve trays and found that tray efficiency was improved significantly [46].
In the 1950's, UCC-Linde also examined tray hydraulic fundamentals such as the onset of spray regime and tray stability, of which only today the distillation industry is starting to appreciate. Bubble promotion devices were incorporated into their trays decades before Koch-Glitsch added them to their Superfrac trays. Finally, truncated downcomer technology was understood by UCC-Linde well before Jim Nye came up with the Nye tray about 1984. Needless to say, UCC-Linde was a "powerhouse" of distillation knowledge that was kept internal to that organization and, only recently, the world is starting to understand that.

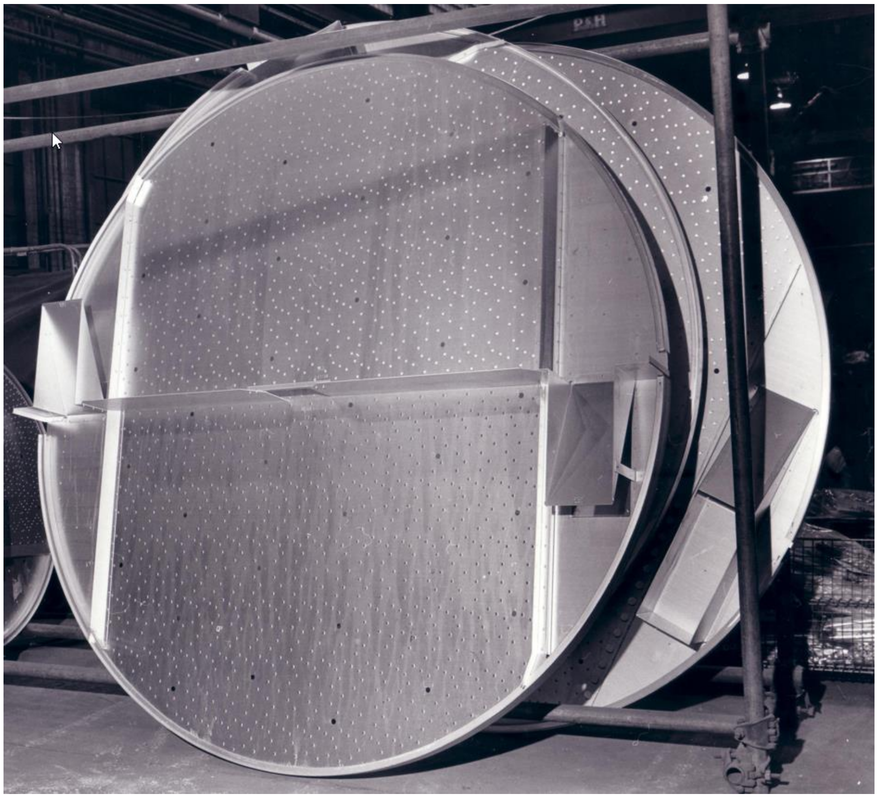

Fig. 5: Typical UCC-Linde Parallel Flow Slotted Sieve Tray for ASU

Full Utilization of the Tray Volume

UCC-Linde (MD™ Trays) and Shell (HiFi™ Trays) both realized in the early 1960's that for highly liquid loaded applications, long outlet weir lengths and truncated downcomers enabled excellent tray capacity. The long weir length reduced the froth height and significantly reduced tray pressure drop. The truncated downcomers enabled more tray cross-sectional area to be devoted to vapor traffic. For more conventional trays, Jim Nye was the first to realize that truncated downcomers could also be employed on them as well. This realization, initiated research into highly sloped truncated type downcomer applications by numerous tray suppliers. What was happening at this time in the distillation equipment industry, was that every cubic centimeter of tray volume was subsequently dedicated to maximizing either vapor and/or liquid capacity. There was no more "wasted" tray vapor volume for droplet settling or "wasted" downcomer liquid volume for bubble buoyancy.

Centrifugal Devices

With this new "wave" of tray developments now utilizing the entire tray volume, it was quickly understood that the new limiting factor on tray capacity was gravity. A tray is a Vapor/Liquid contacting device that has a separator above it (called tray spacing) and a coalescer below it (called a downcomer). Both the "separator" and the "coalescer" are limited in capacity by the force of gravity. There comes a point when the up-flowing vapor momentum is greater than the weight of the liquid on the tray. At this point the "separator" ceases to function and tray maximum vapor capacity is reached. The same applies to the liquid where the momentum of the froth going into the downcomer is greater than the buoyancy of the vapor bubbles trying to get out of the downcomer upon which the "coalescer" ceases to function and the tray liquid maximum capacity is reached. Both the weight of the liquid and the buoyancy of the vapor bubbles are limited by gravity. If a different force can be applied to the tray (e.g., centrifugal force), then additional tray capacity can be achieved. People have been able to do this with the ConSep tray [34] and the Ultra-Frac tray [36] as well as the HiGee tray [37]. The ConSep and the Ultra-Frac trays both use centrifugal force to separate the liquid and vapor before the vapor passes upwards to the next tray. Neither one however enhances the downcomer coalescence. The HiGee tray however enhances both the vapor separation as well as liquid coalescence with higher "gravity" through centrifugal motion of the whole tray. These devices are not low cost, and as engineers, we need to be mindful of cost. However, when a tower's maximum capacity is reached, ConSep trays and Ultra-Frac trays can be applied to continue using the existing vessel. For HiGee, these devices are applicable when space and size is severely limited (e.g., off-shore) and the cost of a conventional tower is prohibitive.

Impingement Devices

UOP came up with the novel idea that instead of using centrifugal force, they chose to utilize impingement force to separate the liquid from the vapor. Above their SimulFlow™ trays [47], they have vane inlet devices that are specifically located to remove the liquid from the up-flowing vapor. The intent here is to also get past gravity as the limiting force in the "separator" section of trays.

Hydraulic Correlations

The original hydraulic correlations for trays simply predicted vapor capacity (jet flood) and pressure drop. However, since the 1970's, a number of additional tray hydraulic parameters have been developed such as; downcomer backup, downcomer capacity, froth aeration, spray regime, stability, weeping, entrainment, harmonic vibration, weir loading, unit reference or percent open valves, vapor cross flow channeling and finally downcomer sealing. [48] [49] [50] [51] [52] [53] These parameters all have recommended limitations or guidelines to maintain good hydraulic performance. Altogether, these numerous relationships can be envisioned on a single diagram called the performance diagram which was originally developed in the early 1960's [54] [55]. The performance diagram has become an extremely useful tray design tool that shows a window of satisfactory operation for trays bounded by the hydraulic parameters listed above and clearly shows the operating flexibility of a given tray device.

From the operating window it can be readily seen that the main determiners of maximum tray capacity are downcomer velocity, weir loading, jet flood and the onset of spray regime. The maximum downcomer velocity is determined by the delta density available. The maximum weir loading is determined by the weir length available and can be manipulated by changing tray passes and employing modified arc (ModArc™) type side downcomers. Maximizing Jet Flood is determined by the available tray spacing and minimizing weir loading as well as reducing tray deck opening's size. Finally, minimizing the onset of Spray regime is determined by reducing dry tray pressure drop and increasing froth height and can be manipulated by changing the outlet weir length with pickets. Turndown is also depicted on these diagrams and shown as weeping, stability and the onset of spray regime.

The MEGA Tower

As demand for refined products increased over the past 100 years, economies of scale dictated that trayed (and packed) towers increased in size. In the past 20 years, the industry has seen distillation towers as large as 17 meters in diameter and 20 meters square (CO_2 capture) [56]. This increase in size requires increased understanding of mechanical strength, multiple beams, and lattice structures. These mechanical features sometime interfere with the functional aspects of trays and must be accommodated. In addition, feed and withdraw devices are larger, take up a large volume in MEGA towers and have become quite complex. The designer needs to be aware that larger equipment designs need to account for the extra distances that liquids and vapors will travel to get to their ideal destinations. In addition, the use of 6 and 8 pass trays with ModArc side downcomers have become commonplace which brings with it, new hydraulic challenges such as flow path balancing [57].

Beyond Trays and Packings

People have been predicting the demise of distillation and the employment of trays and packings for more than 30 years. Membrane technology has already supplanted distillation in desalination because distillation is so highly energy intensive [58]. The AIChE Separations Division has been monitoring the Academic activity in alternative separations techniques and find that 98% of the current Separations papers are regarding alternative separations other than Distillation. With all this activity, it would appear that "the writing is on the wall" and Distillation may eventually become a "Dinosaur" Unit Operation. However, both author's opinions are that this will take several decades. Time will tell.....

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