Performance Evaluation of a Prototype of a Fractal Distributor

A research report
written for purposes of

Amalgamated Research Inc.

Twin Falls, Idaho, USA

by

Dr. Žarko Olujić
Associate Professor

Laboratory for Process Equipment
Delft University of Technology
Leeghwaterstraat 44
2628 CA Delft, The Netherlands

Delft, October 24, 1997

Summary

A fractal geometry based liquid distributor developed originally for large diameter chromatographic columns has been adapted accordingly for counter-current gas-liquid operation. Two configurations, one with a common and the another one with a high density of distribution points were tested using the liquid distributor test facility of J. Montz at Hilden (Germany) and the TU Delft 1.4 m id. column hydraulics' simulator. Results of the study indicated that new design provides potential for achieving the highest quality of distribution at both low and high liquid loads and can be consequently operated at wide turndown ranges (even greater than 10 to 1) without significant loss of the accuracy. Because of a relatively high open area it is suited also for high gas loads. It can be fed by pressure and by gravity and requires less liquid pressure than the common orifice pipe distributors. However, as a typical orifice type device it proved to be sensitive to fouling. It is flat, easy to fabricate (in plastic) and to install.

In other words, the fractal distributor combines advantages of pressure fed orifice distributors and high performance narrow trough distributors. If the cost of a fractal distributor manufactured completely from metal could be comparable to that of common narrow trough distributors, this distributor could make a chance in distillation applications, particularly those requiring an increased density of irrigation and considerable turndown.

Additional relatively simple experimental effort is needed to gather knowledge required for fine tuning of fractal distributor design for low liquid load applications.

INTRODUCTION

The purpose of the work summarised in this report was to evaluate experimentally the potential of a counter-current gas flow prototype of a very promising liquid distributor based on fractal geometry, which has been developed originally by ARI for use in conjunction with large diameter chromatographic columns.

State of the Art

It is well known that the performance of large diameter beds consisting of high performance random and structured packing, particularly those with large specific surface area, strongly depends on the quality of the initial liquid distribution. Large scale maldistribution studies carried out at Delft University of Technology (1) have definitely shown that if the liquid distribution starts wrong in a large diameter column it will end up even worse.

In other words, the key to good liquid distribution in a packed bed is a good initial liquid distribution. This means that from a process standpoint the liquid distributor is the most important packed column internal. A liquid distributor is required at all locations in a packed column where an external liquid stream is introduced. In a distillation column there are always at least two external feeds, reflux and column feed. In case of more demanding separations requiring long beds, inevitable liquid maldistribution is reduced by arranging shorter beds, separated by a liquid re-distributor, which consist of a liquid collecting device and liquid distributor. External feeds can be distributed using pressure or gravity, and to redistribute the liquid within the column gravity-fed distributors are employed.

Obviously, the primary purpose of a distributor is providing a uniform liquid distribution. This means a highly symmetrical cross sectional distribution of so called drip points including the periphery (wall zone) and a uniformity of liquid flow from each of the drip points. However a distributor also must provide enough space for gas/vapour passage to avoid excessive liquid entrainment. Since a structured packing can be successfully operated at very low and very high liquid loads the liquid distributor should have a reasonable flow range (turndown). Also it should be resistant to fouling.

In 1986, Moore and Rukovena (2) recognised the importance of matching the distributor performance with the degree of fractionation required, and introduced a widely accepted method to evaluate the quality of liquid distributors. Various aspects of conventional and high performance distributor design, fabrication, testing, installation, operation and troubleshooting as well as a method of analysis and optimisation of distributor design are described in detail in most recent papers by Bonilla (3) and Klemas and Bonilla (4). Among the designs available only the so called narrow trough distributors appeared to be capable of earning the grade of a high performance distributor, which implies that more than 90 % of the available top surface of a bed of packing has to be uniformly irrigated. This becomes more difficult if a low liquid load operation is required. Anyhow, the narrow trough distributor is suited to large diameter columns and it offers a large open area (≈ 45%) for passage of vapour or gas. It is suitable for high turndowns, which, however requires additional height and in conjunction with large diameters at least one pre-distribution stage placed above distributor is required. Also, an increase in the turndown ratio is always at the expense of distribution quality at both capacity ends. It should be noted that in all cases the cost of distributor increases considerably if the number of distribution points has to be above common 100 or less d.p./m^2.

On the other side, the low height, high open area devices, such as the orifice-pipe distributor and spray-nozzle distributor, are restricted to a relatively low liquid load (below 20 m^3/m^2hr), narrow turndown applications (2 to 1) and offer generally a very poor distribution. In addition to this the spray-nozzle distributors are extremely prone to excessive entrainment at increased gas loads. A relative advantage of the orifice-pipe distributor is that it can be fed by pressure or by gravity, and the later one is preferred when a better quality distribution is required. It is practically not sensitive to variations in levelness, however, increasing the diameter means generally the decrease in the quality of distribution and therefore the use of this simple and relatively cheap device is restricted to columns with diameters below 3 m. Other disadvantages are a relatively large pressure drop and a pronounced sensitivity to plugging.

Nevertheless, the orifice-pipe type of distributor provides one of the best ways to distribute liquid in a packed column. Increasing the quality of liquid distribution accompanied by overcoming the above mentioned limitations would certainly make such a device interesting for applications claimed at present by proven, but more heavy, expensive, levelness sensitive, relatively high narrow trough distributors.

FRACTAL DISTRIBUTOR

The fractal geometry based liquid distributor has been originally invented, designed and manufactured by Amalgamated Research Inc. for industrial scale chromatography applications (5-7). Figure 1 shows schematically the layout of a fractal distributor consisting of three pre-distribution levels and a distribution plate comprising a very large number of distribution (drip) points. The detailed description of the pre-distribution manifold used to provide liquid to the distribution plate with orifices can be found elsewhere (8). This highly symmetric device proved to be capable of providing a nearly ideal uniform liquid distribution in chromatographic applications.

An inherent property of the fractal distributor is that all liquid paths are hydraulically equivalent which means that pressure drop requirements are minimal and turndown range can be much larger than that of similar devices encountered in packed column practice. In addition to this it should be noted that there are no scale up limits, because fractals are self similar structures which exhibit an invariance to scaling. There are also no theoretical limitations with respect to the density of distribution points.

Obviously there are many things here indicating a considerable improvement potential with respect to the distribution quality achievable by so called high performance distributors in counter current gas flow applications. During a brain storming session held at ARI in November 1996, the most important parameters for maximising the performance of packing with a distributor have been reviewed (Olujic). A summary is given in Table 1.

First, most essential step in adapting the original design for counter-current gas flow operation was providing the free area for gas flow. ARI solved this by cutting out the surface of the fractal plate not occupied by liquid distribution channels, and this allowed creation of a considerably large open area. Two prototype distribution plates have been manufactured, a low density one (an equivalent to roughly 100 d.p./m^2) with a free area above 60% and a high density one (roughly 400 drip points/m^2) with an open area of around 50 % (with respect to test column cross section) which is also above that achievable with narrow trough distributors. The drip point density of the so called high density is something required in cases of sharp fractionation's using large surface area random and structured packings.

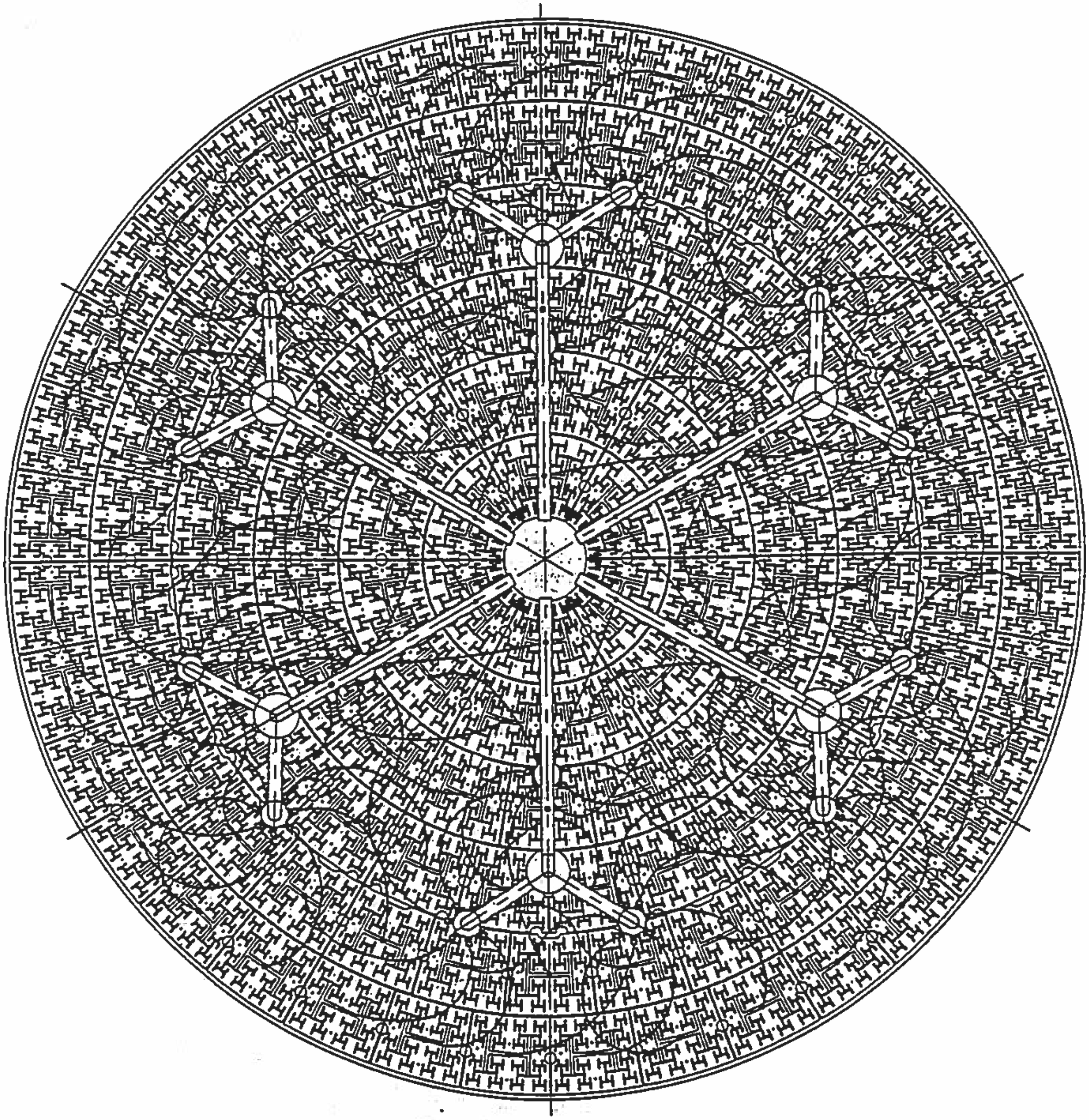


Figure 1 Top view of a fractal distributor with 4032 (1 x 6 x 3 x 7 x 32) drip points

Table 1 Comparison of Fractal (estimated!) vs. Commercial Distributors Performance

Distributor type:	Orifice-Pipe		Spray-Nozzle	Narrow-Trough	Fractal		
Driving force:	Gravity	Pressure	Pressure	Gravity	Gravity	Pressure	
Uniformity	+	o	-	++	++	++	
Turndown	+	+	-	++	+	++	
Free area	++	++	++	+	+	+	
Fouling	-	-	+	+	-	-	!
Residence time	+	++	++	o	+	++	
Installation	+	++	++	o	+	+	!
Levelling	+	++	++	o	+	++	
Distribution density	+	+	++	+	++	++	
Height requirement	o	++	++	-	o	++	
Mechanical integrity	++	++	++	+	o	-	!
Construction material	+	+	+	+	-	-	!!
Entrainment	+	o	--	+	+	o	!
As re-distributor	o	--	--	++	o	--	!
Column diameter	o	+	++	+	o	++	
High purity applications	+	-	--	++	++	++	

! indicates potential uncertainties/worrying factors in case of FD, requiring evaluation in practice.
++ excellent, + good, o satisfactory, - less satisfactory, -- bad.

A manifold and two distribution plates have been shipped to Delft for testing. The primary objective of our experimental effort was evaluate both distributors with respect to the quality of liquid distribution, turndown range, and the sensitivity to entrainment at higher gas loads.

EXPERIMENTAL

Distributors Tested

The two distribution plates of the prototype distributor have a diameter of 1.32 m, which is chosen to fit into the Delft University test column with an internal diameter of 1.4 m, taking care that the periphery holes are located at a distance of 50 mm from the column walls. Figure 2 shows a photograph illustrating the layout of two different distribution plates, one with 144 and the other one with 576 equidistantly placed distribution points. The open areas are 60 and 50 % (with respect to column cross section!), respectively, which is considerably more than achievable with common high performance trough distributors. As can be seen from Fig. 2 the distributor plates consist of 3 concentric rings containing elementary distribution cells, one with 4 and the other one with 16 equidistantly placed orifices/holes. The dimensions of the holes/orifices are 6.4 and 3.2 mm, respectively. The size of cells is slightly different in two outer rings. From constructional reasons, the cells in the immediate centre of distributor are different than in the concentric ring sections.

The manifold of the distributor tested is shown in Fig. 3. As illustrated, liquid flows from the

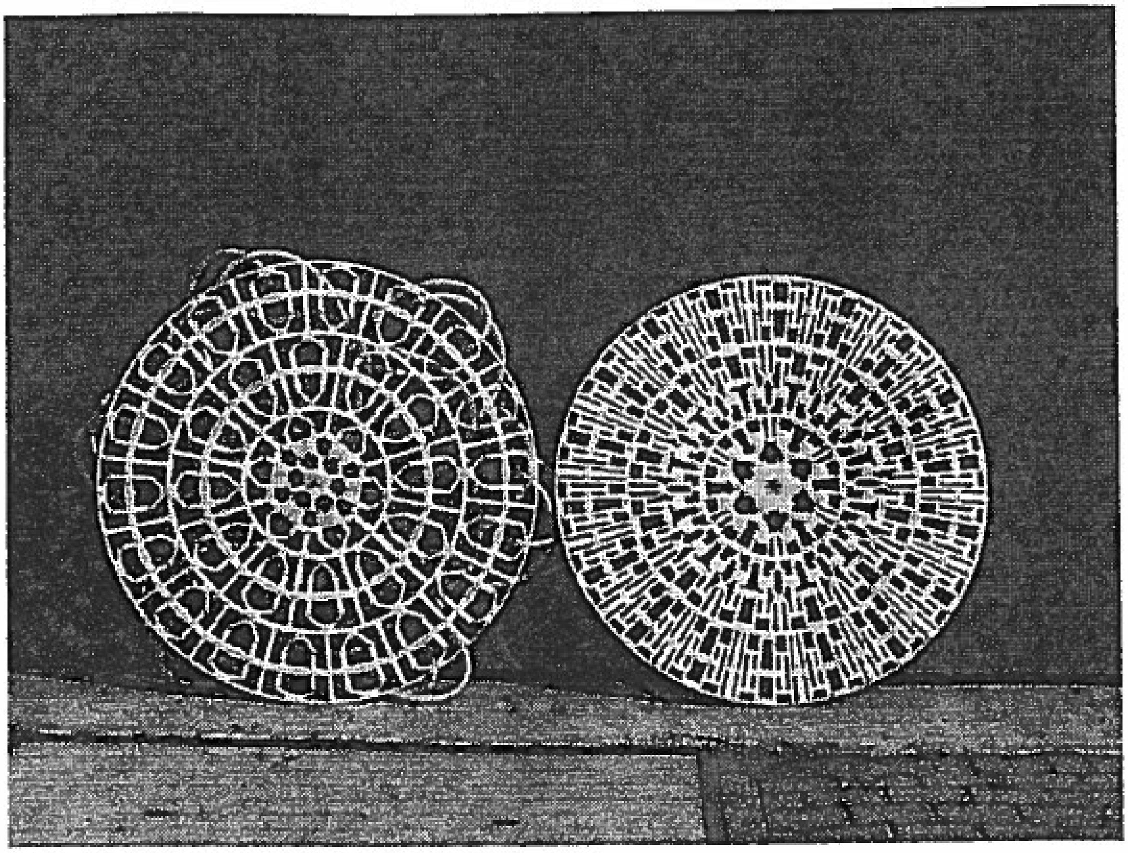


Figure 2 Layout of low- and high drip point density distribution plates

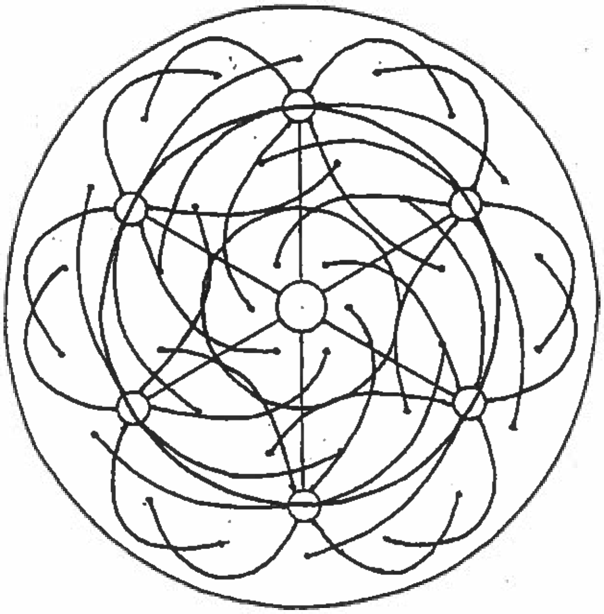


Figure 3 Schematic illustration of the manifold of the prototype of the fractal distributor

central divider through six equivalent conduits to the satellite dividers. Each satellite divider feeds six of the in total 36 distribution cells contained in the fractal section, i.e. distribution plate. The connection between the satellite distribution centres and the distribution cells is ensured in this case using flexible, plastic tubes of the equal length plugged from above. A side view of the installed manifold is shown in Fig. 4, indicating considerable inconsistency in the levelness of plastic tubes connecting satellite pre-distributors with distribution cells. The satellite distribution centres are not visible, because of the fact the bends of plastic tubes extend well above the level of distribution centres, which must be avoided in final design.

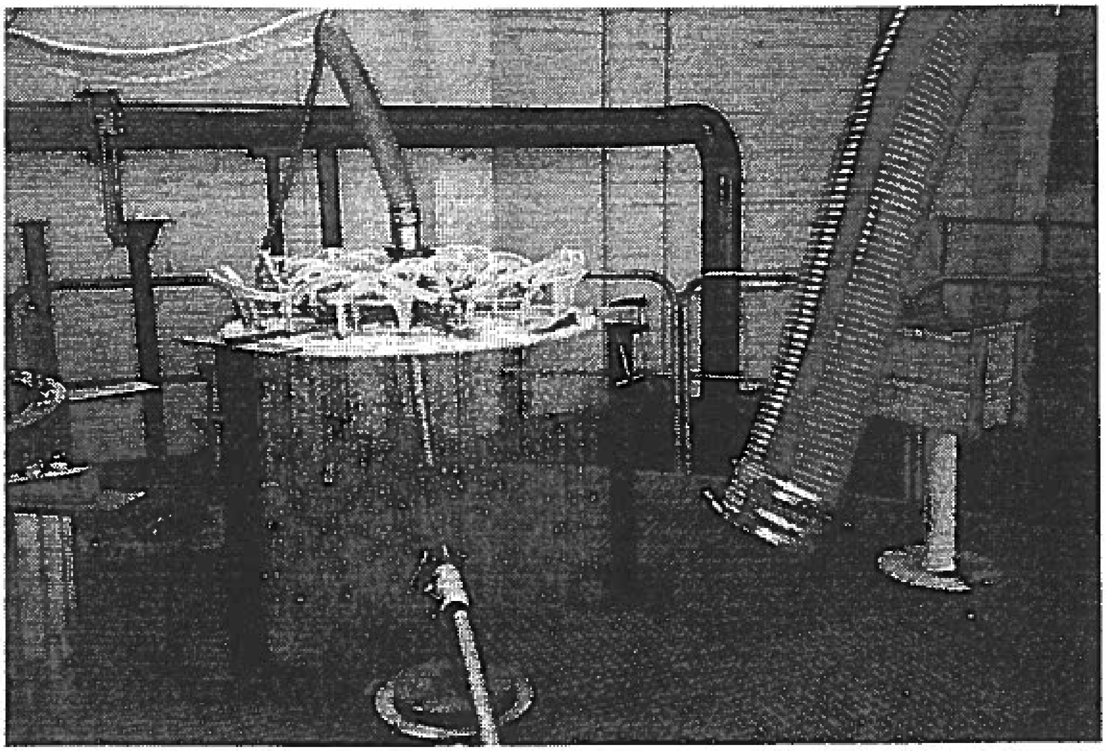


Figure 4 Photograph of the fractal distribution in action, on the platform of the J. Montz distributor test stand in Hilden, Germany

Total height of the distributor delivered, from the bottom of the distribution plate to the top of the inlet flange, is 0.15 m, however the installation height is inevitably larger, because of the height required for the connection with the liquid supply line.

Experimental Set-up

A typical distributor test implies measuring flow through each orifice or distributor section, which depends on the size of distributor. In order to do this over a large range of liquid loads we made use of the distributor test facilities of Julius Montz in Hilden, Germany. This renown structured packing manufacturer supports the ongoing research work on the Delft University of Technology in this field. Fig. 4 shows a simple liquid collecting device equipped in this case with a narrow funnel, which can be placed below each of the distribution points, and is connected via a tube with the liquid collecting compartment. A stopwatch was used to measure the time needed to fill a certain volume. Point-by-point measurements have been carried out with small density distributor and each second point has been measured in case of the high density distributor. Examples of measurements protocol are given in the appendix, together with a copy of a protocol of a large turndown narrow trough distributor designed for TU Delft column. The numbers indicate millilitres of water collected within given time interval (usually 10 seconds). A statistical analysis of test data has been made to express accordingly the observed variation of the flow between the drip points.

The major purpose of the test in Delft was to observe and to quantify the liquid entrainment in conjunction with high gas loads. This has been done for a low and a moderate liquid load with both distributors. A vane type mist eliminator with liquid drainage system was employed to measure the entrainment rate as a function of gas load. The diameter of the test column made of Plexiglas (see Fig. 5) is 1.4 m and the available pump and fan enable loads up to 100 m^3/hr water and 25000 m^3/hr air, respectively.

All experiments (in Hilden and Delft) have been carried out at ambient conditions, and the person involved was our graduate student M. Kroon.

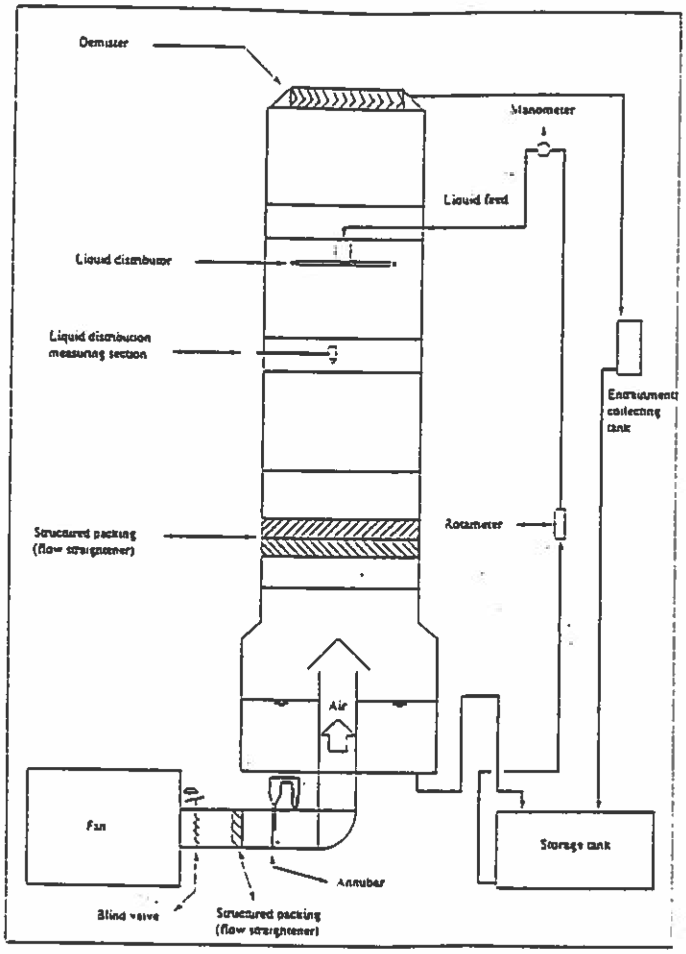


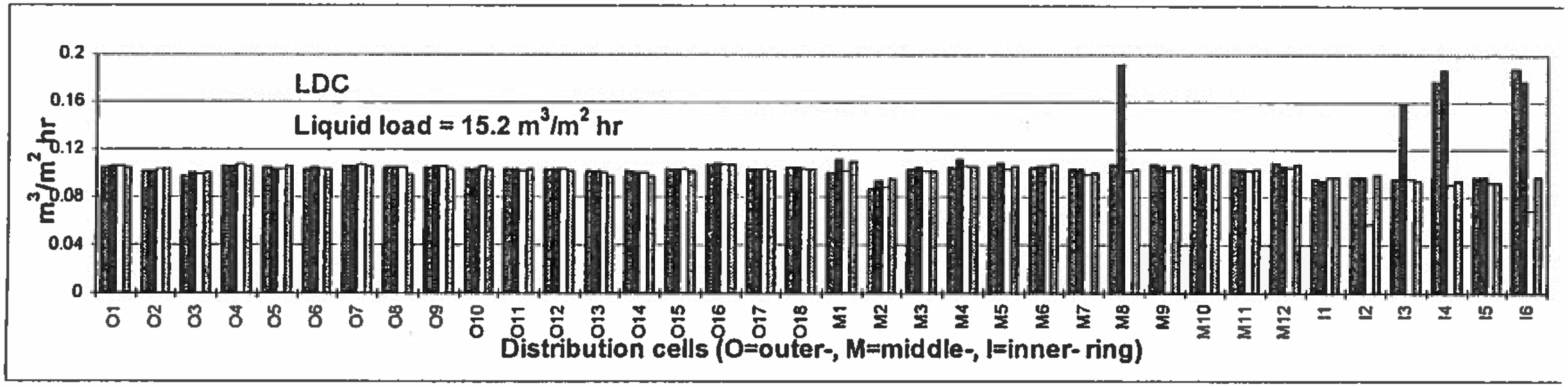
Figure 5 Schematic illustration of the TU Delft column hydraulics' simulator (d = 1.4 m)

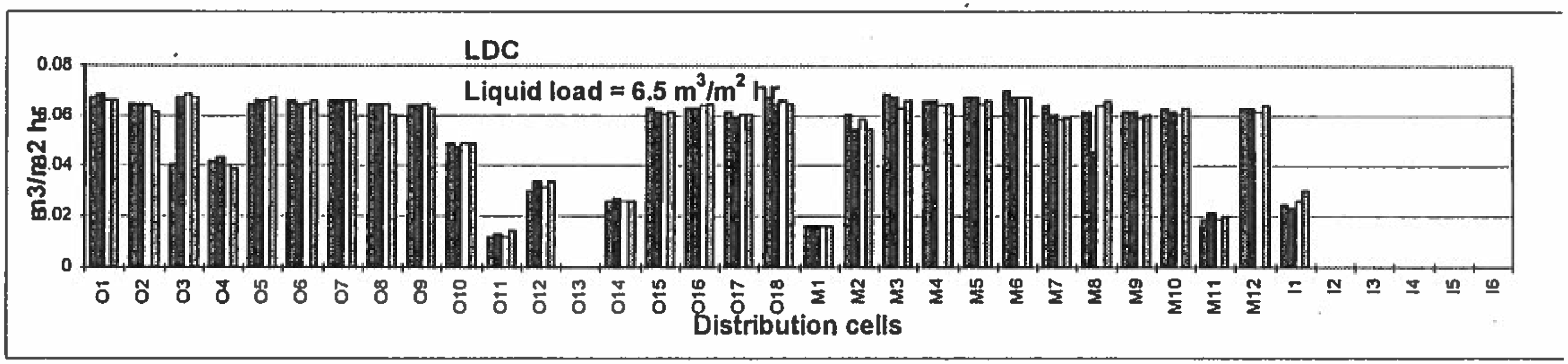
RESULTS AND DISCUSSION

Figures 6 and 7 show the distribution quality expressed as average superficial liquid velocity for each distribution point/cell for 3 characteristic liquid loads (low, medium and high) for the low- (LDC = low density configuration) and high (HDC = high density configuration) density distributor, respectively. It should be noted that the applied liquid load range covered a turndown ratio of 9, and that the low load is somewhat above- and the high load well above the design limit. Obviously, the best performance appeared to be that around the design point (medium) liquid load. In both cases the performance of central part (zone) appeared to be a problem. At low liquid load LDC appeared to be prone to considerable maldistribution in each of concentric segments. This indicates a sensitivity to deviations in pressure drop imposed by differences in elevations of plastic cell supply tubes. At the lowest liquid load the bends in supply tubes feeding the central zone cells were that high that liquid was not able to overcome the height and get into these cells. The same occurred with cell O13 in the outer ring. At increased liquid load the distribution quality improved considerably, with exception of few holes. Striking is a very good performance of HDC at medium load, with only few cells under-irrigated in case of low and high liquid loads. But this applies only to outer and inner concentric ring of distribution cells, while the central zone appeared to be seriously overloaded at all liquid loads (see Fig. 7). This can be avoided by adapting accordingly the layout and the number of holes in the central zone, and the disturbing effect will cease gradually with increasing diameter. Anyhow, the observed disturbances are of minor relevance and can easily be removed which will consequently help to improve the overall distributor performance beyond the limits of accuracy adopted as standard for high quality of liquid distribution.

In general, the data obtained in Hilden, evaluated later on in Delft, indicated a worrying degree of maldistribution. After some evaluation it became obvious that vertical fittings are the wrongdoer. This has been communicated to ARI and shortly after a set of elbow fittings arrived. The low density distributor has been re-equipped and installed above the column adapted in this case for point-to-point measurements (see Fig. 8). In this way it was reached that no one of the bends of the connecting tubes was above the level of satellite distribution centres. Figure 9 compares the measured liquid distribution profile with that obtained in Hilden for the worst case, i.e. low liquid load.

Obviously, the improvement is such that we can talk about a nearly uniform distribution. Striking is also a remarkably good performance in the central zone. Small, practically unimportant discrepancies are due to a remaining, relatively small degree unlevelness of plastic tubes. Namely at low liquid loads this distributor, designed for a large turndown, is not running full, i.e. it operates practically as a gravity distributor so that it becomes extremely sensitive to unlevelness. In other words, connecting the satellite centres with distribution plates must be considered as a crucial installation point and solved appropriately. Absolute must is to keep the connecting tubes below the level of satellite distribution centres. Another worrying factor, in case of operation at low liquid loads in conjunction with high turndown range design or, in general, with high density applications, is the hole itself. Namely, the discharge from a hole depends strongly on the method of making a hole. First of all the deviations in hole diameter should be kept within 10%. Also the edges of the entrance and outlet side of the hole should be mechanically as clean as possible. It should be realised that at low liquid loads the surface tension may also play a role, i.e. affect the pattern of liquid leaving the hole. At high liquid loads the atomisation of liquid leaving the hole is a potential danger, because this could promote excessive entrainment. This aspect of fractal distributor performance has also been investigated experimentally.





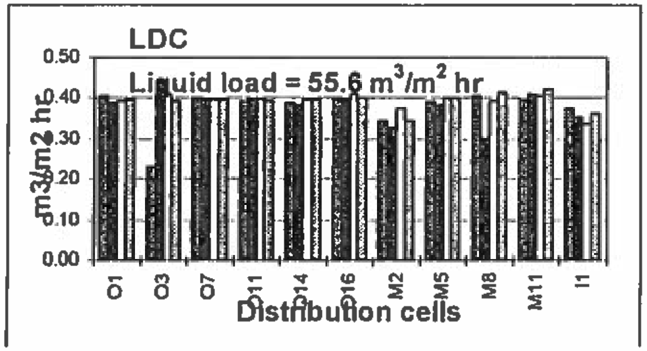


Figure 6 Liquid distribution quality (local drip point velocities) of the low density distributor as a function of the liquid load

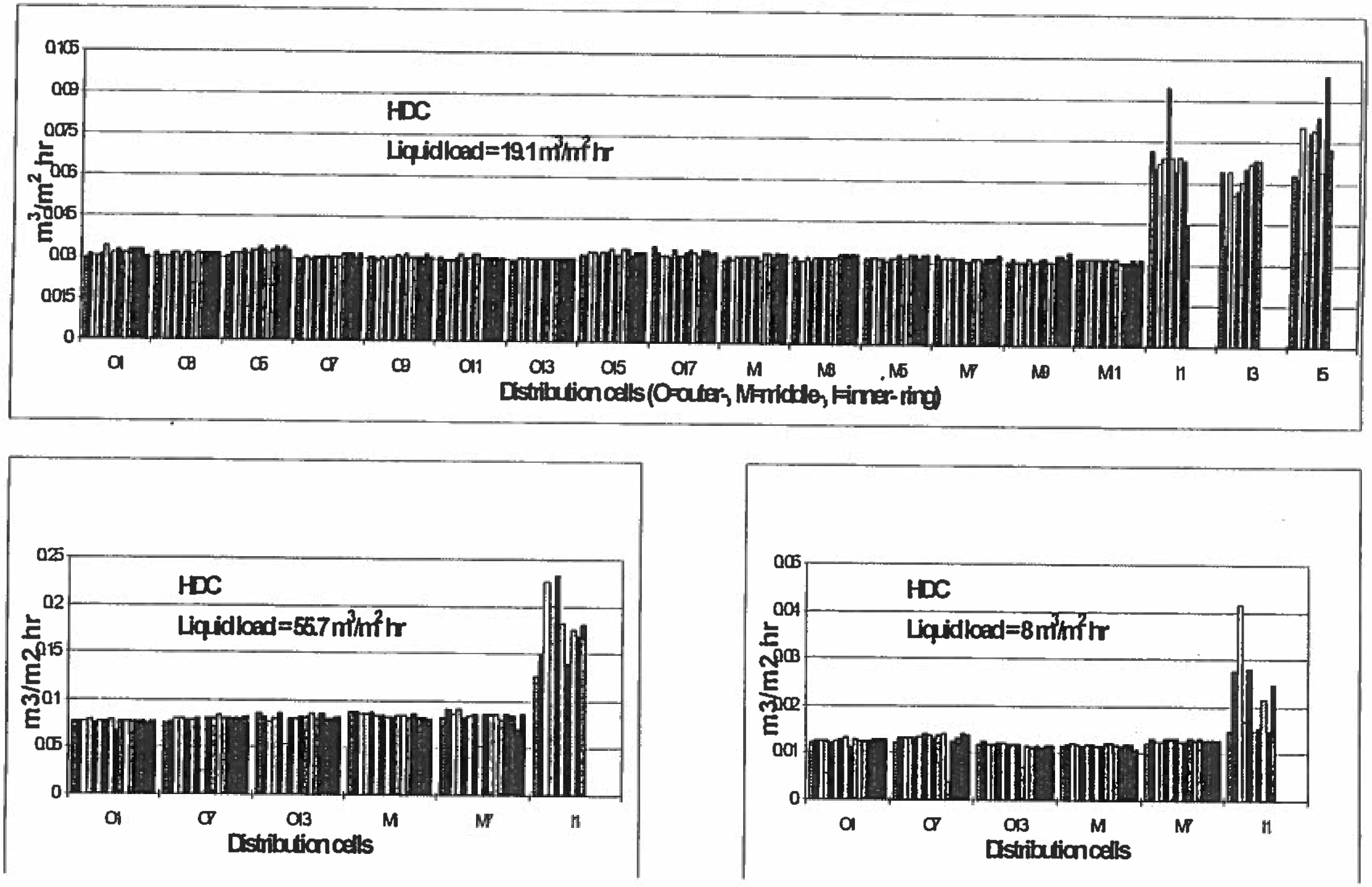


Figure 7 Liquid distribution quality (local, drip point velocities) of high density distributor, as a function of liquid load

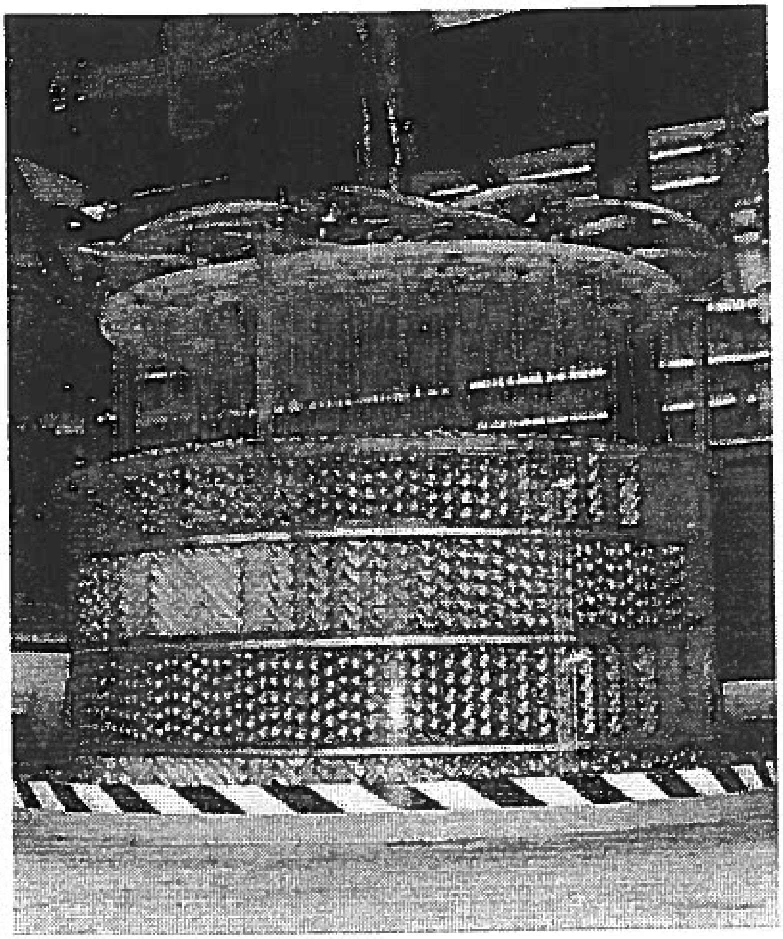


Figure 8 Photograph of the low drip point density (100 d.p./m^2) fractal distributor equipped with elbow fittings (placed above a bed of Montz-pak B1-250 in the TU Delft 1.4 m diameter column hydraulics' simulator)

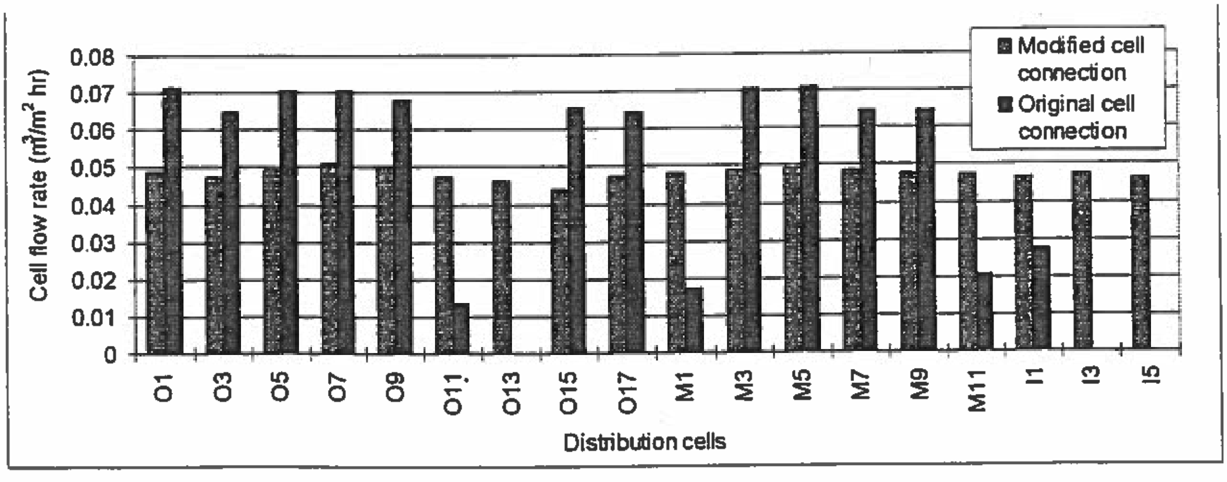


Figure 9 Comparison of low liquid load performances of original and modified (elbow fittings) LDC

The counter-current gas flow operation tests are summarised in Fig. 10, showing the fraction of entrained liquid as a function of gas load expressed as gas flow factor. In general, within the range measured the quantity of liquid entrained is practically negligible. Obviously, at high gas loads the quantity of entrainment increases, and this is more pronounced in case of the high density (HDC) than the low density (LDC) configuration. The same occurs with the effect of liquid load. It should be noted that open area of LDC is considerably larger than that of HDC, and the corresponding liquid jets more stable, i.e. less prone to disintegration and entrainment of droplets. Having in mind the established relation between the drip point density and the size of surface area of packing (2), it can be concluded that entrainment rate will be negligible in practice even when operating well beyond the loading point. Namely, the onset of flooding in packing and consequently entrainment from the top of the packing will occur at lower gas load than the entrainment from distributor itself. This implies that this kind of distributor is also suitable for use in combination with high capacity packings (low surface area and large inclination angle).

Starting the high capacity pump, after one year of non-activity, has been accompanied by pumping a certain volume of fouled water containing rust and other debris. This consequently got into the high density distributor causing plugging of a number of orifices. This way we came to a simple demonstration of the sensitivity of the fractal distributor (an orifice type device) to plugging. This proved to be the only potential operational problem we experienced during the testing, which however can be avoided in practice by placing the filters in distributor supply lines.

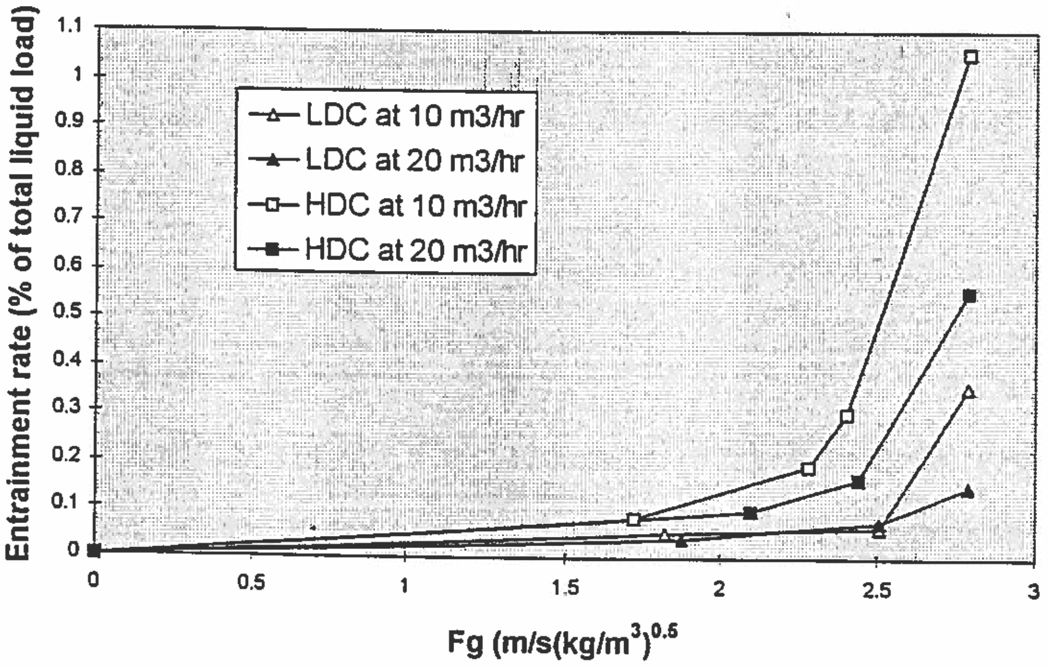


Figure 10 Liquid entrainment rate as a function of gas load and liquid load, as measured with low- and high density configurations , respectively

CONCLUDING REMARKS

Two prototype fractal geometry based liquid distributors have been tested to evaluate their potential for application in counter-current gas-liquid operations. After necessary modifications in the connections of cell supply lines, the liquid distribution proved to be within that considered as high quality (<5% deviation) over a large turndown ratio. Even in case of high density distributor it appeared possible to have a quite large free area for gas flow, i.e. in the range of that achievable with narrow trough distributors. In other words, fractal distributor integrates advantages of both pressure driven orifice-pipe distributors and the gravity driven narrow trough distributors. However, as a typical orifice device it is sensitive to plugging/fouling. In other words, fouling represents the only real threat for the performance of FD.

With respect to other open uncertainties and questions (see Table 1), it can be concluded that:

Installation itself is not a problem and should be considered together with the overall design. It should be noted that the distributor segments must be narrow enough to enter the column through a manhole. Connections between distributor segments have to be strong enough to ensure mechanical integrity.

The most sensitive constructional point remains to be the material of construction of distribution cells/plates. Use of polyethylene or some other plastic material eases manufacture and reduces costs tremendously, but limits the field of application seriously. If one wishes to enter the world of warm applications like most of distillations and fixed bed reactors the distribution cells must be made from metal or a feasible alternative found. In any case, a metal construction will be much more demanding and consequently more expensive. A relatively simple solution, at least for normal distribution density situations, could be the use of prefabricated rectangular metal tubes cut to desired lengths and welded to each other to shape the desired inclined "H" structure. It is a work intensive effort, however it could be a feasible solution for most common distillation applications. A symmetrical two level manifold is good enough as final solution for distribution densities below 100 drip points per m^2.

With respect to entrainment the performance appeared to be well above the expectations.

Because of the need for external pumping a pressure driven distributor is not suitable for liquid redistribution purposes, which may be considered as a serious limitation. Application of FD as a re-distributor requires a gravity driven operation, which is connected with increased height requirements. A simple experiment is needed to establish the correlation between the height and the turndown.

Another point to be considered is the performance achievable below the minimum load encountered in this study (below 5 m^3/m^2hr, going down to 0.5 m^3/m^2hr or less), i.e. in the range typical for vacuum distillation applications, where large specific surface packing are often employed. In this range, the smallest details around hole design can play a crucial role. Simple single distribution cell experiments are needed to find the proper hole design and size, and optimise with respect to desired turndown.

If ARI decides to manufacture the fractal distributor then the finished products must be tested to prove the proper performance. For this purpose ARI should consider building a simple distributor test facility.

Acknowledgement

We are obliged to J. Montz GmbH from Hilden, Germany, for allowing us to make use of their distributor testing facilities. We also greatly acknowledge the contribution of our mechanical engineering student Michiel Kroon who has carried out this work as a part of his graduation programme at TU Delft.

Literature cited

1. Olujić, Z., F. Stoter, J. de Graauw, "Measurement of Large Scale Gas and Liquid Maldistribution in Structured Packings", IChEME Symp. Ser. No. 128, B151 (1992).
2. Moore, F. and F. Rukovena, "Liquid and Gas Distribution in Commercial Packed Towers", Chemical Plants and Processing, No.8, 11 (1987).
3. Bonilla, J. A., "Don't Neglect Liquid Distributors", Chem. Eng. Prog. 89, 3, 47 (1993)
4. Klemas, L. and J. A. Bonilla, "Accurately Assess Packed-Column Efficiency", Chem. Eng. Prog. 91,7, 27 (1995)
5. Kearney, M., K.R., Petersen, T. Vervloet and M. W. Mumm, U.S. Patent 5,354,460 to The Amalgamated Sugar Company (Oct. 11, 1994).
6. Kearney, M. and V. Kochergin, "A Uniform Distribution System Based on Fractal Geometry" presented at the AIChE Annual Meeting, Miami Beach (1995)
7. Kearney, M. and V. Kochergin, "A Liquid Distributor for Industrial Chromatography Columns: An approach based on fractal geometry", Proc. of the 5th Congress of Chemical Engineering, San Diego, July 14 to 18, 1996, Vol. 1, p. 377.
8. Cox, J.R., and E.G. Bulgin, U.S. Patent 4,999,102 to The Amalgamated Sugar Company (Mar. 12, 1991).

Appendix

Examples of the measurement protocol used in this study: A1: LDC, A2: HDC, and A3: Narrow trough distributor.

Plates and Channels for Low Density Config.

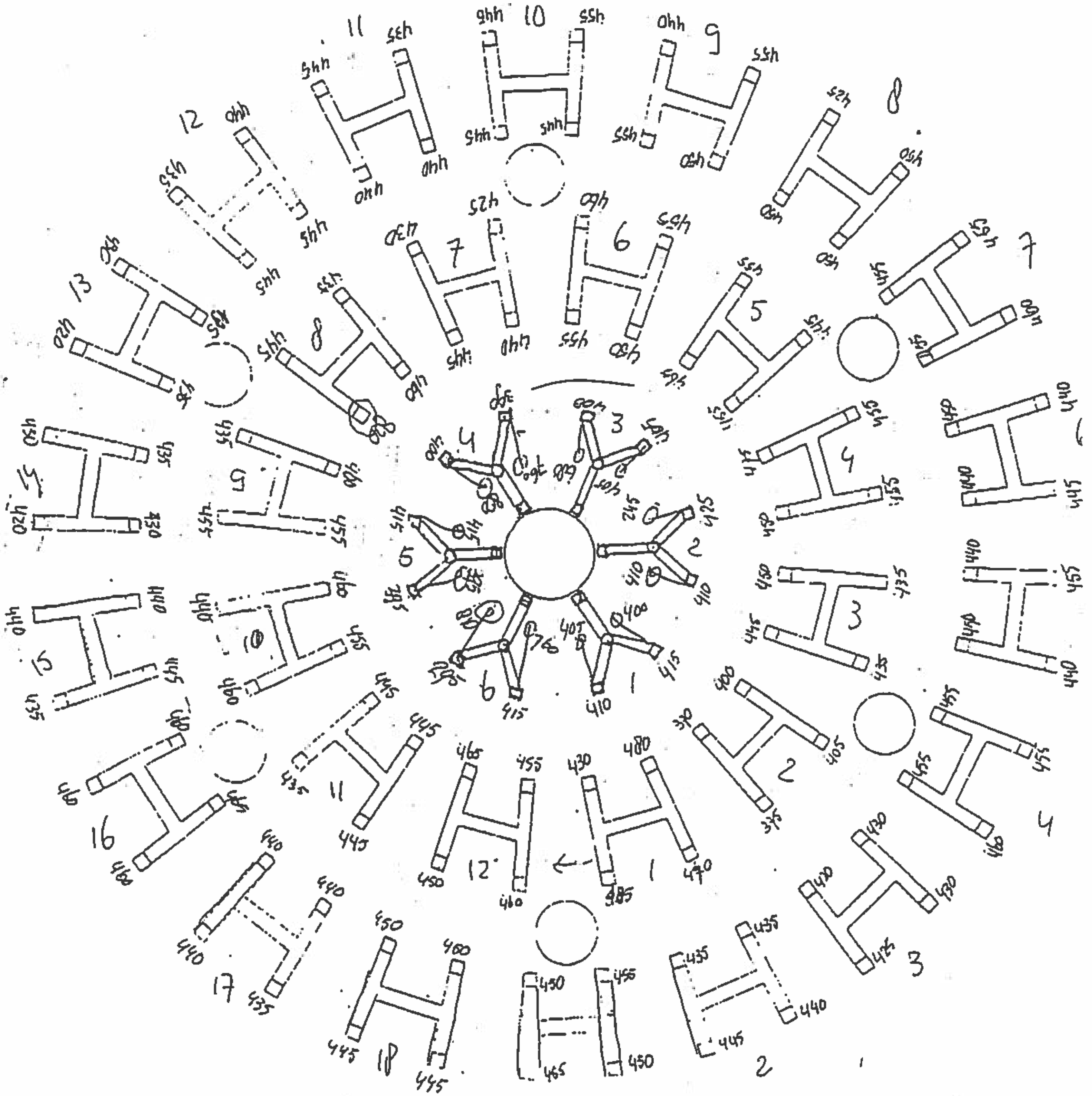


Figure A1 Measurement protocol of LDC (medium liquid load)

Plates and Channels for High Density Config.

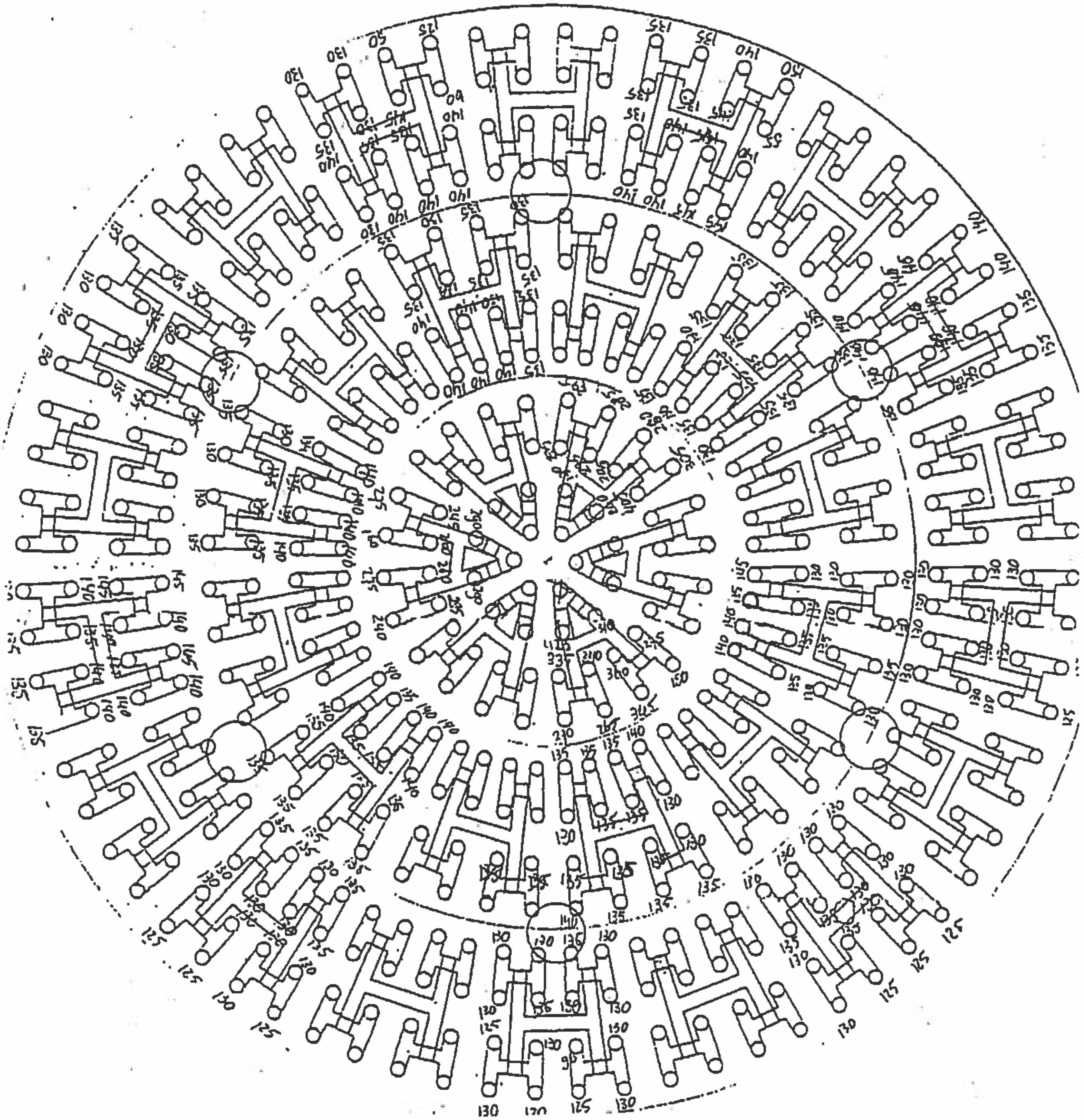
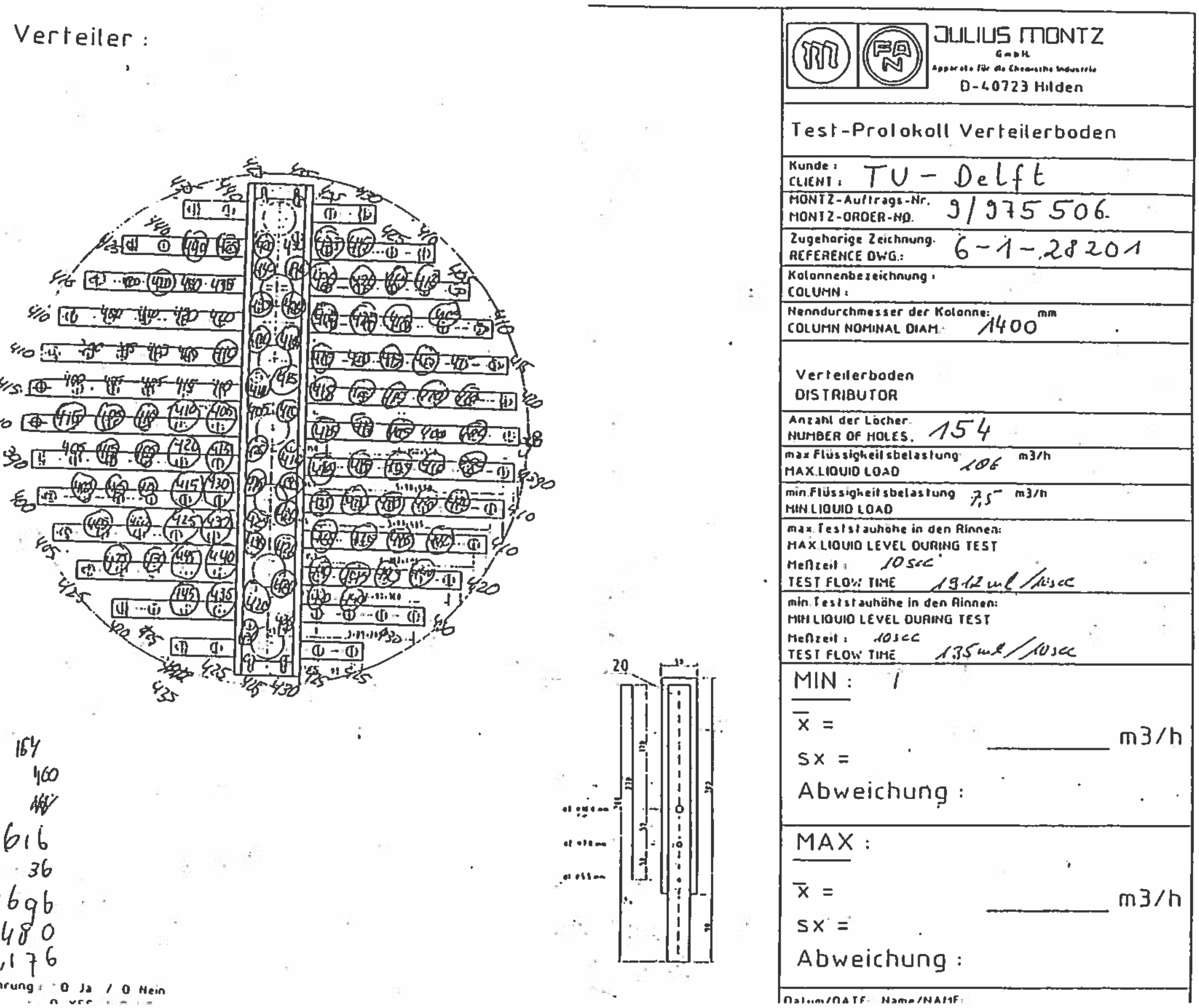


Figure A2 Measurement protocol of HDC (medium liquid load)



JULIUS MONTZ GmbH
Apparate für die Chemische Industrie
D-40723 Hilden

Test-Protokoll Verteilerboden

Kunde : CLIENT :	TU - Delft
MONTZ-Auftrags-Nr. MONTZ-ORDER-NO.	9/975 506.
Zugehörige Zeichnung. REFERENCE DWG.:	6-1-28201
Kolonnenbezeichnung : COLUMN :	
Nenndurchmesser der Kolonne: mm COLUMN NOMINAL DIAM.	1400
Verteilerboden DISTRIBUTOR	
Anzahl der Löcher NUMBER OF HOLES.	154
max Flüssigkeitsbelastung m3/h MAX.LIQUID LOAD	106
min.Flüssigkeitsbelastung m3/h MIN LIQUID LOAD	7,5
max.Teststauhöhe in den Rinnen: MAX LIQUID LEVEL DURING TEST Meßzeit : TEST FLOW TIME	 10 sec 1912 ml / 10 sec
min.Teststauhöhe in den Rinnen: MIN LIQUID LEVEL DURING TEST Meßzeit : TEST FLOW TIME	 10 sec 135 ml / 10 sec

MIN : 1

$\bar{x}$ = ________ m3/h

sx =

Abweichung :

MAX :

$\bar{x}$ = ________ m3/h

sx =

Abweichung :

Datum/DATE: Name/NAME:

Leerlaufbohrung : O Ja / O Nein
DRAIN HOLE : O YES / O NO

164
160
[illegible]
616
36
3696
18480
22,176

Figure A3 Measurement protocol of Montz narrow trough distributor (design point load, turndown 14 to 1)