EXPERIMENTAL CHARACTERISATION AND CFD SIMULATION OF GAS DISTRIBUTION PERFORMANCE OF LIQUID (RE)DISTRIBUTORS AND COLLECTORS IN PACKED COLUMNS

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ABSTRACT

The usability of a state of the art CFD simulation package as a tool for analyzing the fluid-dynamic performance of internals encountered in packed distillation columns, such as initial gas distributors, liquid distributors and liquid collectors is demonstrated. A 1.4 ID column hydraulics simulator was used to provide detailed experimental evidence on the gas distribution pattern imposed by various types of column internals. The comparison of measured and predicted profiles for single gas flow conditions indicates a strikingly good agreement.

Keywords: *Packed columns, gas distribution, liquid collectors, liquid distributors, CFD*

INTRODUCTION

Large diameter packed columns are well established in distillation and related applications and are found in columns with diameters up to 14 m. It is well known that the potential for both gas (vapour) and liquid maldistribution increases as column diameters increase [1]. The problem with liquid maldistribution is that large diameter beds are not capable to restore to health in case of a large-scale initial maldistribution. To avoid this, for sharper separations a flow rate variation per irrigation (drip) point is set to a maximum of $\pm$ 5% of average flow. Although the gas maldistribution can also reduce column efficiency this is seldom the case in practice. Namely, due to a relatively much larger extent of lateral spreading and mixing of gas phase imposed by a relatively low pressure drop, even more pronounced initial maldistributions are smoothed out easily. In addition, unlike the liquid phase the gas phase during the flow through a packed bed tends to maintain a uniform distribution once it has been established. Indeed, a controlled gas maldistribution (total reflux distillation) study carried most recently at FRI [2] indicated clearly that even severe forms of initial vapour maldistribution have no effect on packing efficiency and capacity.

It is a general belief that more pressure drop means more uniformity in both initial and bed gas distributions. Certainly, the pressure drop of distribution devices is a major parameter in design considerations, however there is no clear criteria regarding the quality of initial gas distribution. Anyhow, useful information regarding the performance of gas distributors and related design rules can be found in open literature [1, 3-9]. Publications based on results of comprehensive experimental studies carried over years in Delft using small and large-scale equipment provide detailed insight into the extent of lateral spreading and mixing of gas in structured packing beds [10-14]. Certainly, gas maldistribution can be induced in an irrigated bed by existing liquid maldistribution. There are only few publications dealing with the depth of penetration of initial gas maldistribution [7, 9, 15-16]. Regarding the development of means for characterisation of flow maldistribution a valuable contribution is the recent paper by Billingham et al [17].

In a packed column, the gas phase entering the bottom part of the column through a distributor ascends toward the top of the column passing through two or more irrigated packing beds separated by the liquid redistribution sections. Liquid is provided at the top through a liquid distributor, most frequently a narrow-trough one. To reduce the detrimental effect of unavoidable liquid maldistribution, the upper limit is usually set to a bed height equivalent to say 15 theoretical stages. Upon leaving a bed the liquid is collected, mixed and redistributed to the bed below. Common redistribution sections consist of a liquid collector/gas redistributor placed at a short distance below a bed and a liquid distributor placed immediately above the following bed. The liquid collector is designed to collect the liquid with minimum interference with the upcoming gas flow, and to deliver it in the most appropriate way to the liquid distributor below. By the virtue of an irrigated packed bed, gas entering the liquid redistribution section is uniformly distributed. In general, a redistribution section should maintain the quality of gas distribution established for initial gas distribution. To perform accordingly, both liquid distributor and collector must have a large open area and this must be distributed evenly across the column cross section to ensure proper gas distribution. Narrow trough liquid distributors used frequently these days offer up to 50% free area for gas. Some vane (chevron) type liquid collectors arrive at same values, however in case of chimney tray devices the free cross section area goes often down to 25% only. This introduces correspondingly larger pressure drop and this fact is often considered as a guaranty for a good gas distribution quality. Unfortunately, there are no explicit criterions for the quality of initial gas distribution and none is reported in open literature on the extent of initial gas maldistribution generated by liquid (re)distributors and collectors.

There are some other reasons for a greater concern in this respect. To save the vertical space designers tend to reduce the distance between the liquid collector and the bed. In this respect a chevron or vane-type collector, which is expected to act as a gas distributor, offers advantages over a traditional chimney tray collector [3]. Yet the main advantage of this device is a high open area, i.e. a relatively much lower pressure drop, which makes it suitable for vacuum applications. Therefore the vane-type collectors are used predominantly in combination with structured packings. This is presently done in conjunction with installation of high capacity packings, which at the same loads operate at considerably lower pressure drop than standard packings. With further reduction of already low pressure drop per unit height, the driving force for lateral spreading and mixing of gas diminishes considerably. For high capacity packings with surface areas of 250 m^2/m^3 or less this may mean that there is practically no intrinsic means left in the bed to suppress imported (initial) gas maldistribution. Hence the design practices have to be re-evaluated and improved accordingly.

A major development step in this direction is the employment of commercially available Computational Fluid Dynamics (CFD) based tools. Certainly there are some doubts about the usefulness of CFD with respect to the complexity of the two-phase flow situations as encountered in practice. Anyhow, at present stage of development it is generally anticipated that the ability of simulating appropriately the single-phase gas or liquid flow pattern as imposed by the geometry of common column internals will provide valuable information for designers of large diameter columns.

On the other hand, it is also widely recognised that proper experimental validation is a prerequisite for the development of the necessary confidence with respect to achievable accuracy and reliability of CFD simulations. With this in mind, some five years ago a multi-sponsor research project was started at the Delft University of Technology, oriented toward collecting necessary experimental evidence, at largest feasible scale.

The main purpose of this paper is to present some revealing experimental evidence on gas distribution performance of liquid (re)distributors and collectors, and to show that a commercial CFD package can be used with confidence as a means for predicting the extent of initial gas maldistribution in packed columns induced by the geometry of these column internals.

EXPERIMENTAL

The gas flow (mal)distribution related experiments were performed with ambient air. A detailed description of the column hydraulics simulator with the internal diameter of 1.4 m can be found elsewhere [18-20]. Figure 1 shows a side view and a top view of the experimental set-up employed for the measurement of gas velocity distribution across the cross section of the test column. A conventional pitot-tube was used for this purpose. The pitot-tube was programmed to move automatically in regular time intervals over a rectangular measurement grid. The numbers shown in the top view picture indicate the measurement points for the coarsest grid (16 cm spacing) employed, however in the present study only the results obtained with finest grid are

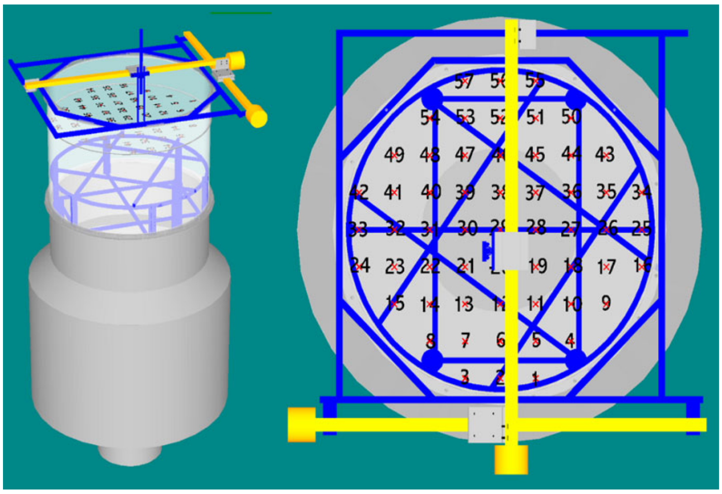

Figure 1: Side and top views of the set-up for velocity distribution measurement.

shown. The fine grid with spacing of 2.5 cm contains 2450 measurement points per column cross section, and approximately 14 hours are needed to complete a run.

Bottom section bed was 2 m deep and consisted of the corrugated sheet structured packing Montz-Pak B1-250, placed on the support structure clearly visible in Fig. 1. Measurements were executed first to establish the velocity distribution profile leaving this bed and as reported elsewhere [19] this profile appeared to be uniform. Then a large turndown, narrow trough liquid distributor with 145 drip tubes, was placed on the bed. A 3-D drawing shown in Figure 2a illustrates the design of this distributor. In conjunction with this liquid distributor three different liquid collectors were used: two versions of a vane-type collector, with blade inclinations of 60^0 and 80^0 respectively (see Fig. 2c), and a common chimney tray collector (Fig. 2d). Above the collector, a 1m bed of the same packing was installed and upon it a large flow rate liquid distributor of type VKG (Fig. 2b). Table 1 contains information on the percentage of available free area for gas flow for these devices.

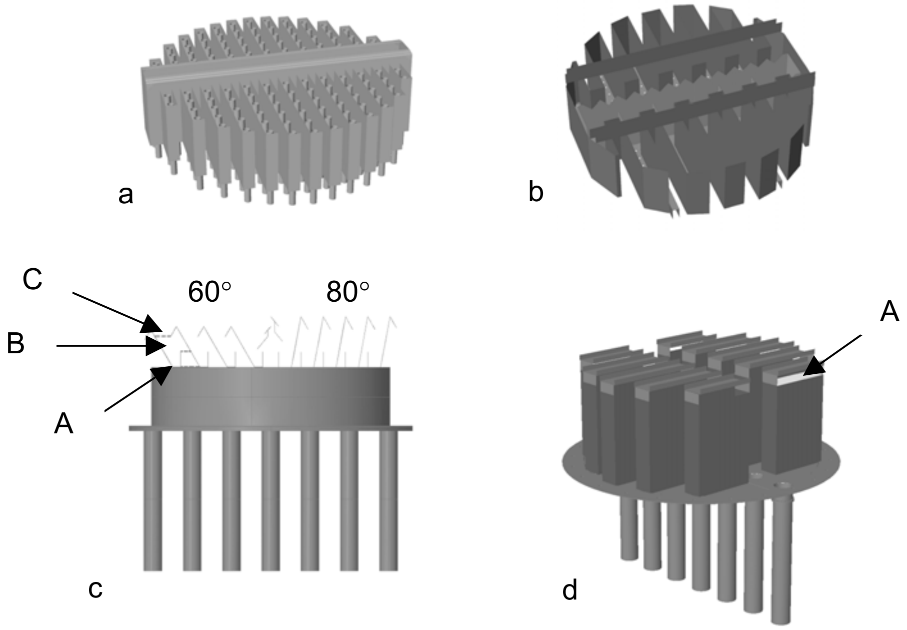

Figure 2: A 3-D impression of the column internals used in this study:
(a) a narrow trough liquid distributor, (b) a VKG liquid distributor, (c) a vane type liquid collector, with different blade inclination angles, and (d) a chimney tray liquid collector.

For each of the liquid distributors/collectors employed in this study the velocity profile was measured immediately above the device (1-2 cm) as well as at a distance (30 – 40 cm) corresponding with the position of next device or packing. The obtained profiles are shown as 2-D plots made in Excel, with a spectrum of colours indicating the ranges of characteristic velocities.

In order to quantify the level of the gas maldistribution accordingly, the use was made of both the coefficient of variation (C_v) and the maldistribution index (*MI*). Background information about these two maldistribution characterisation means can be found elsewhere [17,20].

Table 1: Percentage of available open area for gas flow for the column internals shown in Figure 2

Open area available for gas (%)					
	Narrow Trough L.D.	VKG L.D.	L.C. 60°	L.C. 80°	L.C. Chimney Tray
A	42.0	36.0	41.5	25.6	25.0
B	-	-	24.3	19.2	-
C	-	-	38.3	34.8	-

CFD MODELING SET-UP

All simulations were carried out using the commercial CFD code Fluent 5. Geometry's and mesh preparations were made in Gambit 1.3. As mentioned before, the profile entering the liquid redistribution section was assumed to be a plug flow profile. All simulations presented here correspond to a superficial column velocity of 2.5 m/s, i.e. an F-factor of 2.7 m/s $(kg/m^3)^{0.5}$ or $Pa^{0.5}$.

Thanks to the observed high symmetry of measured profiles it was possible to reduce the computational effort to reasonable limits, by simulating one-quarter of the liquid distributors and/or collectors only. Figures 3a-3e show the unstructured mesh as employed for these simulations. Light flat surfaces indicate the position of the two

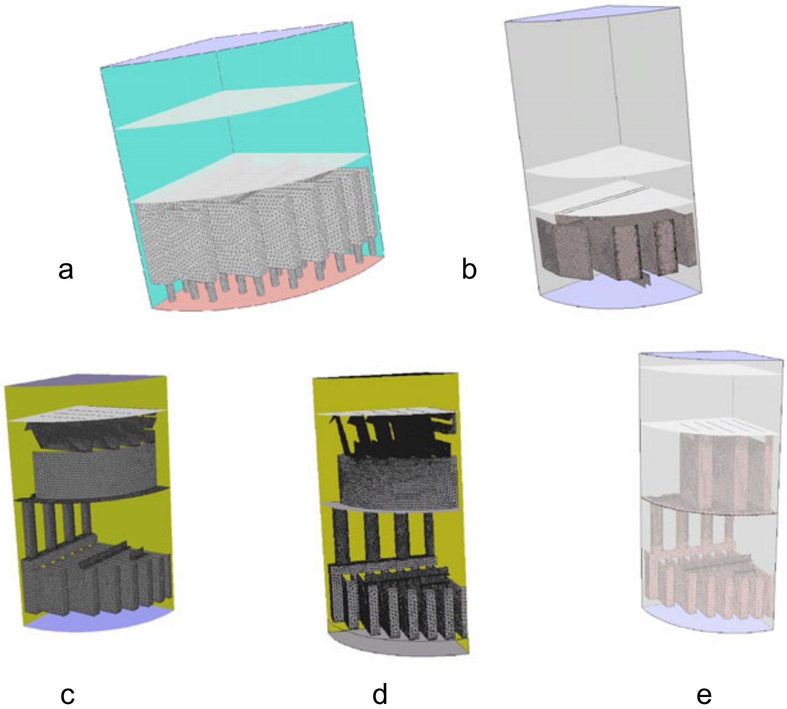

Figure 3: 3-D unstructured grid models established in Gambit 1.3 for Fluent simulations of the gas flow around: (a) a narrow trough liquid distributor, (b) a large liquid load (VKG) liquid distributors, and vane-type liquid collectors with (c) 60° and (d) 80° blade inclination, and (e) a chimney tray liquid collector.

characteristic cross sections. The drip tubes, which were included during simulation of the liquid distributor alone, were omitted from the simulation of the liquid collector/distributor combination to reduce the computational effort. Per device, more than 500,000 unstructured grid cells were employed in conjunction with standard k-ε turbulence model with default settings. A PC with a 650-Mhz processor and a 640-Mb RAM was used for this purpose. Typical run times were around 20 hours. Results of all simulations are shown as full circle 2-D coloured plots. It should be noted that there are slight differences in colors used for velocity ranges by Fluent and those employed in the 2-D plots of experimental data made in Excel. In black and white prints, the black areas denote zones of no velocity, while the light areas represent zones with low to high velocity. In the latter case increasing darkness denotes increasing velocity.

RESULTS AND DISCUSSION

Gas Flow around Liquid Distributors

Figure 4 shows a comparison of calculated and measured gas velocity profiles at two characteristic cross sections above the narrow trough distributor. Here and as well as in the following figures, the “lower” profile shows the situation immediately (2 cm) above the distributor, and the “upper” one that corresponding to the position of the bottom of the liquid catcher. From both calculated and measured profiles leaving the

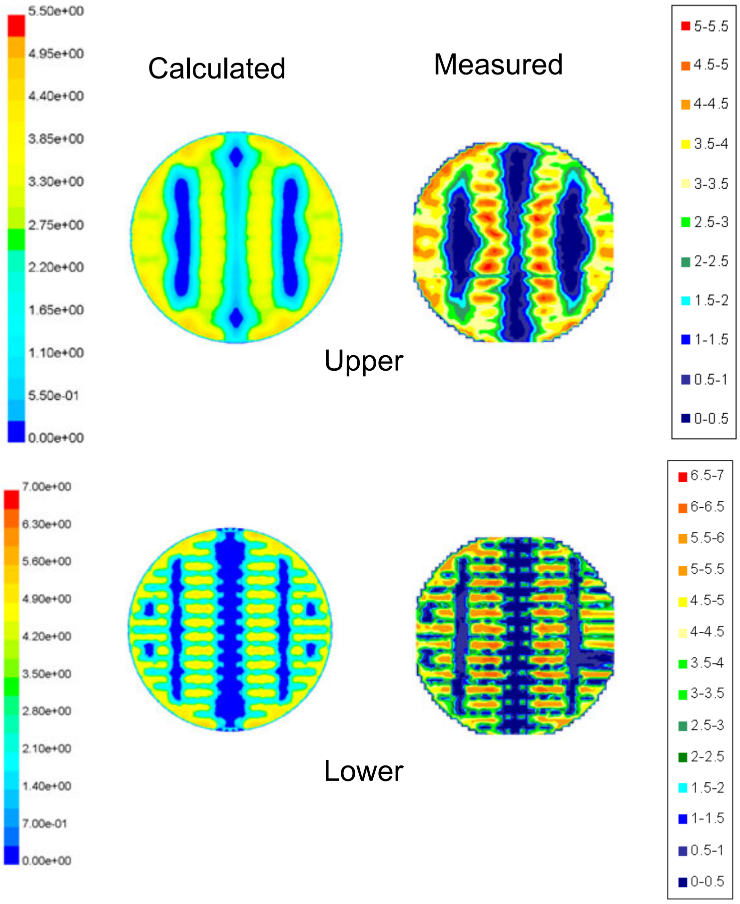

Figure 4: A comparison of calculated and measured gas velocity profiles at two characteristic cross sections above the narrow trough liquid distributor.

distributor, the structure of the distributor can be recognized. Elongated dark (blue) areas oriented perpendicularly with respect to the orientation of troughs represent transversal bars used to keep the troughs together. Due to high velocity created in narrow gas passages between troughs and sharp edges of transversal bars relatively large dead zones behind the bars are created, which persist and become even larger at a distance from the distributor. Measured profiles indicate a more pronounced difference between high and low velocity zones, than the calculated ones, however the flow distribution patterns are nearly identical. The sharp distinction between evenly distributed low and high velocity zones fades away with distance from the distributor. Some 30 cm above the distributor, high velocity gas jets cluster into three major larger velocity zones surrounding three, practically no-velocity zones. This change in the nature and extent of maldistribution is visible in the corresponding values of the maldistribution factor and maldistribution index, shown in Table 2. Due to the formation of three rather large high velocity zones, the low *MI* value associated with the profile leaving the distributor increases by a factor of 3.5, indicating a strong deterioration in the quality of spatial gas distribution. On the other hand, due to reduction in the range of velocity variations the C_v value improves accordingly, but the value of 55% is so high that it indicates the existence of a maldistribution of immense magnitude.

As shown in Fig. 5, similar situation is with the gas distribution profiles generated by the large liquid load distributor. This distributor comprises less but much wider troughs to accommodate large liquid flows, thus leaves less area for gas flow. This leads to higher velocities at both levels, and, as shown in Table 2, correspondingly larger C_v values. Again, a comparatively higher *MI* value of the outlet profile deteriorates, but in this case by a factor 2 only, indicating roughly the same extent of spatial maldistribution, but somewhat worse in terms of C_v values.

Obviously both types of the liquid distributors induce a high degree of maldistribution in the gas phase, which strongly increases spatially but decreases in magnitude with the increasing distance from the distributor body.

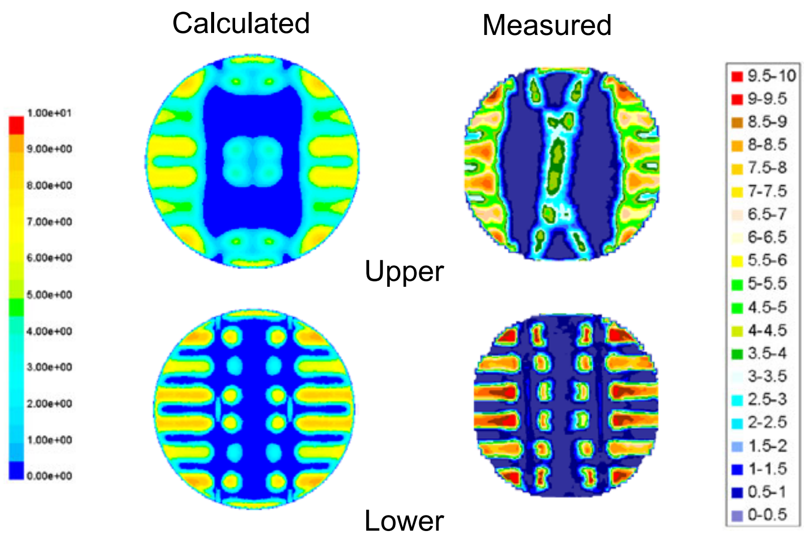

Figure 5: A comparison of calculated and measured gas velocity profiles at two characteristic cross sections above the VKG liquid distributor

Gas Flow around Liquid Collectors

Obviously the liquid collectors receive a highly maldistributed gas profile, however in their designs there are usually no special provisions made to alleviate maldistribution generated from the liquid distributor. From Figures 6 to 8, it becomes obvious that neither a low- nor a high pressure drop liquid collector can bring any improvement in this respect.

Figures 6 and 7 show the comparison of measured and calculated velocity profiles for the vane-type liquid collectors with respectively 60^0 and 80^0 inclination of blades. The agreement is again surprisingly good. Gas flow patterns of two devices are similar and follow the layout of blades. In both cases the profile leaving the collector transforms into a kidney-like profile at the level of the packing support. Again, by clustering an even worse spatial distribution is created, with increasing the distance from the device. Indeed, as shown in Table 2, rather high *MI* values increase by a factor two and more. According to corresponding C_v values, this is accompanied by a certain decrease in the range of velocity variations, which is more pronounced in case of more streamlined collector. It is striking however that there is practically no gas flow in kidney-like zones, and that the velocity in peripheral zones is around 5 m/s. Side cut snapshots of the gas flow in redistribution section, shown in Fig. 9, indicate that such an immense maldistribution is generated by the flow deflecting action of inclined blades, which is more pronounced in case of blades with 60^0 angle. This may mean that in industrial practice gas enters a bed much more maldistributed than anticipated so far for this kind of more or less streamlined liquid collectors.

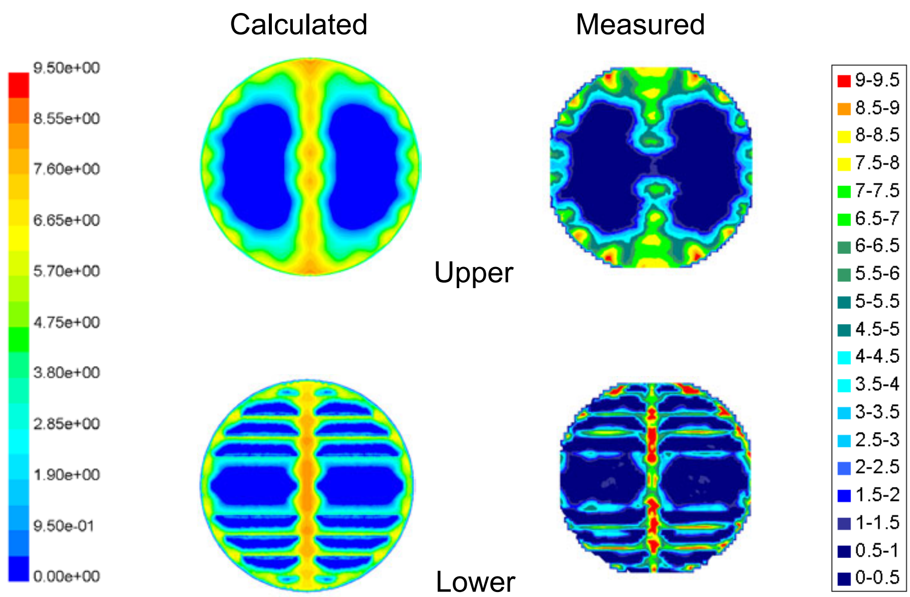

Figure 6: A comparison of calculated and measured gas velocity profiles at two characteristic cross sections above the 60° vane-type liquid collector

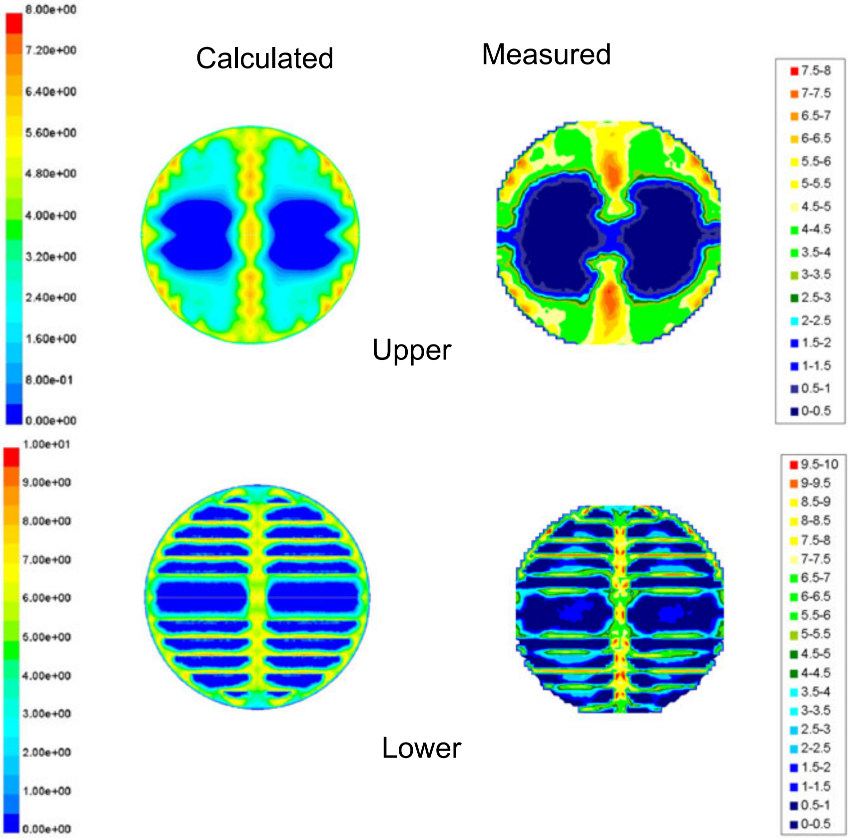

Figure 7: A comparison of calculated and measured gas velocity profiles at two characteristic cross sections above the 80° vane-type liquid collector

Figure 8 shows the measured and calculated profiles for the chimney tray liquid collector. Overall agreement between measurement and simulation is very good and again the simulation generates a difference between high- and low velocities, which is lower than in reality. A major difference with respect to performance of vane-type collectors is that outlet high velocity jets converge into a main stream of gas located in the centre of the cross section, leaving four empty zones at periphery. The reason for this can be seen in Fig. 9, which shows also a side cut profile of redistributor section with chimney tray collector. Namely, in the spaces in between neighbouring gas risers, highly accelerated outlet gas streams deflected by gas riser covers impinge and direct each other in upward direction, creating narrow gas jets with velocity peaks reaching up to 15 m/s. Through strong energy dissipation, these peaks disappear with increasing distance from the chimneys and at a height of 30 cm transform into a velocity plateau with an average velocity of around 4 m/s. This is somewhat lower velocity than that found in high velocity zones generated by vane type collectors at the periphery of the cross section area. Anyhow, the corresponding C_v and MI values indicate that the degree of the maldistribution is about the same as that produced by vane-type collectors, which is somehow surprising regarding the fact that a considerably larger pressure drop (around 50%) is associated with operation of the chimney tray collector. The corresponding dry and wet pressure drop curves are shown in Fig. 10. At a liquid load of 20 m^3/m^2h the pressure drop of the chimney tray collector increases approximately by 20% with respect to that measured at dry conditions. For the 80^0 vane-type collector this increase appeared even larger (around 30%), while a relatively much smaller increase (less than 10 %) observed

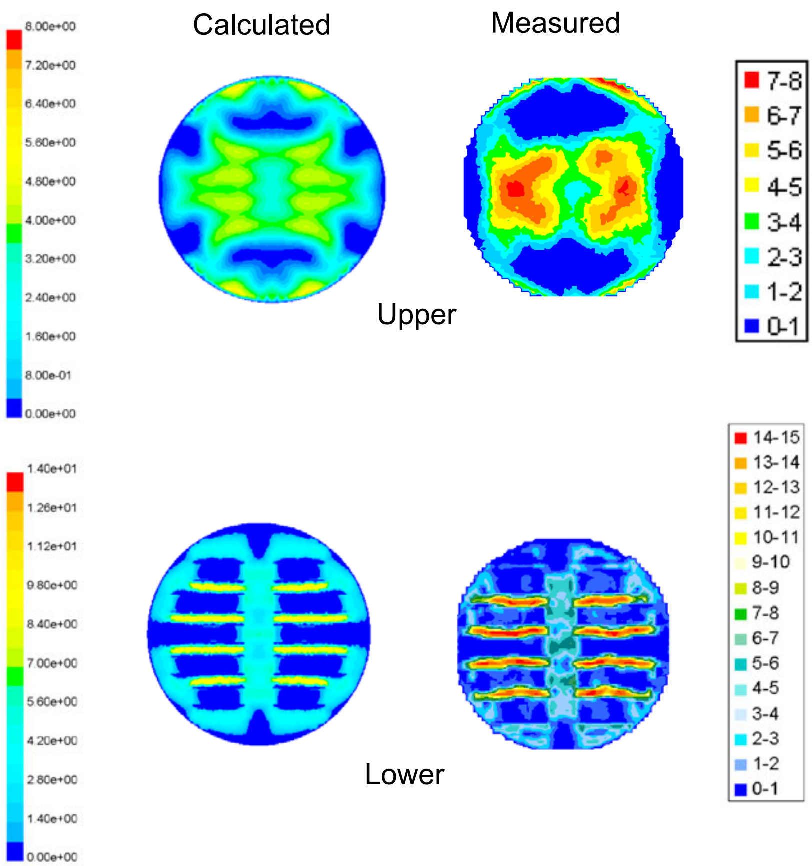

Figure 8: A comparison of simulated (left) and measured (right) gas velocity profiles at two characteristic cross sections above the chimney tray liquid collector

with the 60^0 vane-type collector indicates a rather limited interference of two phases. From visual observations it became obvious that the distance between blades plays an important role here. Namely, in case of narrow spacing as encountered in case of the 80^0 vane-type collector, the liquid curtain bridges over the distance between neighbouring blades forcing the gas stream coming from below to escape laterally toward the open periphery or the central trough. Similar behaviour was also observed at higher liquid loads accompanied however by a much more violent interaction of phases at higher liquid loads, with gas and liquid jets impinging on column walls and all this is accompanied by an excessive entrainment. This made the pressure drop measurement nearly impossible, and at highest liquid load employed (50 m^3/m^2h) the pressure drop remained practically unchanged, but the characteristic change in the slope of the pressure drop curve indicated some kind of loading behaviour. It should be noted that the loading point of the collector coincided in all cases with that of the bed above, however the associated pressure drop was roughly one half of that of a 1 m bed. The corresponding pressure drop curves are shown in another paper [20] discussing the relation between inlet gas maldistribution and the pressure drop of a bed.

So it appears that pressure drop of the distributor itself is not a direct measure for the quality of initial gas distribution, as generally believed. It seems to be more important that the gas flow area is maximised and distributed uniformly across the column cross section and provisions are made to minimise the impinging or a to strong deflection of gas jets. Regarding the chimney tray collector used in this study, it should be noted that the utilised layout is not the optimal one. Namely, it was arranged to fit into already existing redistribution section configuration designed originally for vane type liquid collectors.

Certainly, because of the absence of any downstream pressure drop the observed maldistributions may be considered as the worst case. However, as suggested by Suess [6], only a slight improvement, if at all, can be expected from the effect of liquid draining from the bed. More probably, as observed in our wet experiment, the liquid deflected by strong gas flows will pour out of the bed predominantly in the regions of zero or rather small gas velocity.

Table 2: Coefficient of variation (C_v) and the maldistribution index (MI) at different column cross sections for the internals used in this study

Column Int.	Narrow Trough		VKG		L.C. 60		L.C. 80		L.C. CT	
Distance (cm)	1	30	1	30	1	40	1	30	1	30
C_v	84	55	117	90	117	95	112	79	122	80
MI	2.0	6.8	3.7	6.4	3.2	7.6	2.7	7.8	4.2	6.5

Observed profiles and corresponding maldistribution factor and maldistribution index values suggest somewhat "paradoxal" situation. Namely, with increasing distance from the source of maldistribution a pronounced decrease in the magnitude of velocity variations is accompanied by a strong deterioration in spatial distribution of the variations. However, Fig. 9 suggests that this is something imminent to layout and operation of common liquid collectors in high gas velocity situations. Fortunately, as demonstrated in another paper [20], such a large, but highly symmetrical initial maldistribution is smoothed out within two structured packing layers, and consequently should not be detrimental to efficiency of a bed consisting usually of 20 or more packing layers.

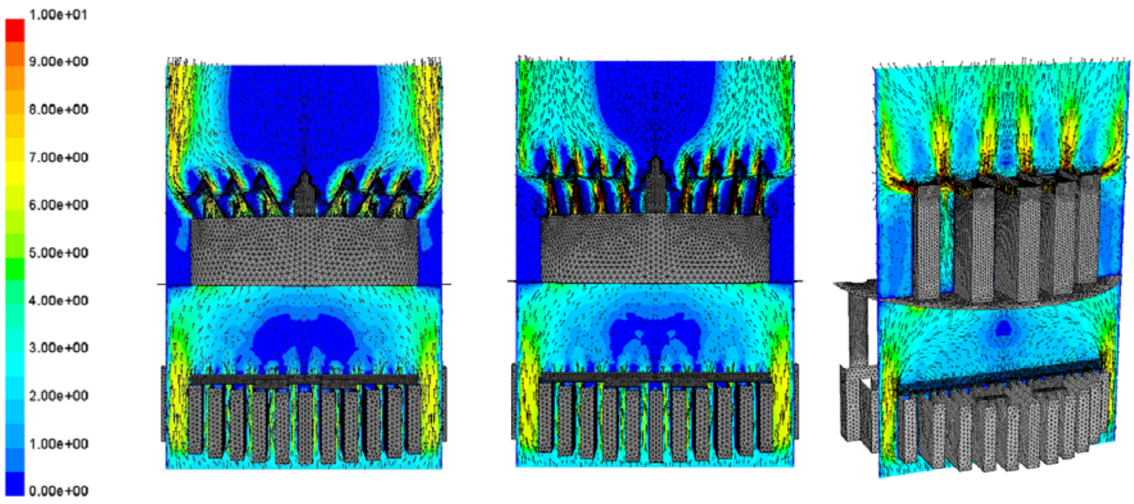

Figure 9: CFD snap shots of a side cut of the gas flow through liquid redistribution section equipped with liquid collectors employed in this study

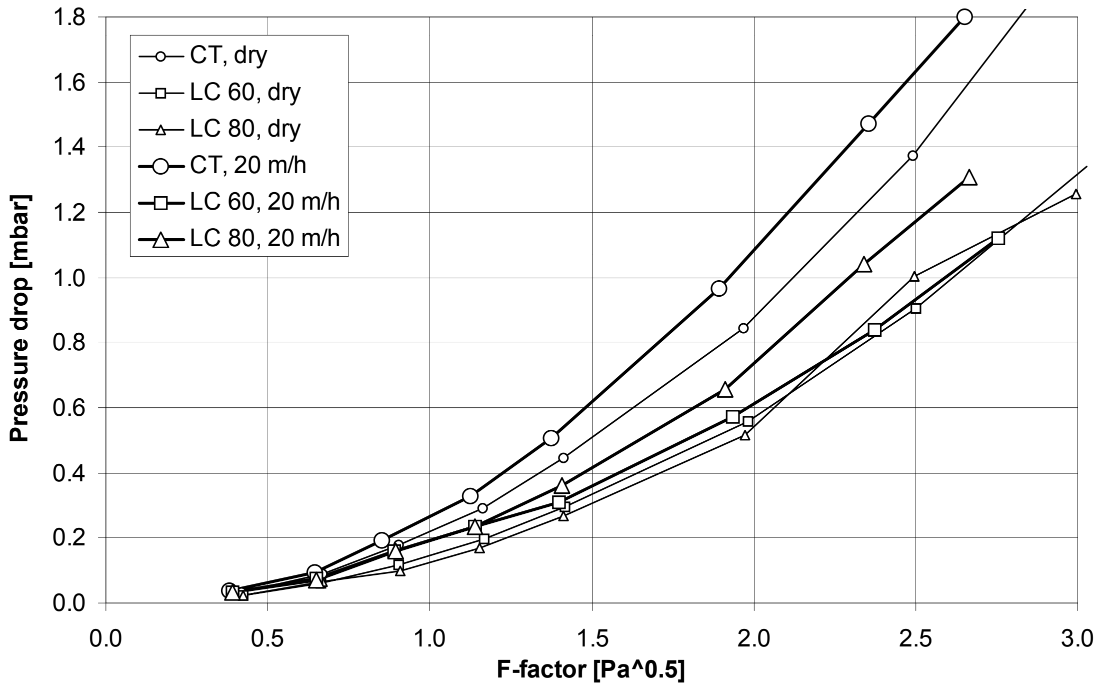

Figure 10: Dry and wet (20 m/h) pressure drop of the three liquid collectors employed in this study.

CONCLUSIONS

A large-scale single flow experimental study has been carried out to collect the evidence necessary to validate CFD models and to establish the degree of reliability of CFD as an engineering tool/aid for design of packed columns/internals.

Simulations and measurements have been performed with two common types of liquid distributors and liquid collectors. The coefficient of variation (C_v) used in conjunction with the maldistribution index (*MI*) gives a good indication of the extent of gas maldistribution induced by the internals involved.

Both, low and high-pressure collectors evaluated in this study cause a strikingly large extent of maldistribution of gas flow. Similar behaviour can be expected under wet conditions.

Regarding the good agreement achieved between simulation and measurement of single gas flow patterns, CFD tools like Fluent may be considered as a useful aid for design and evaluation of performance of packed column internals. Nevertheless, the immense run time associated with CFD simulations may work adversely to potential users.

ACKNOWLEDGEMENTS

Authors would like to thank: BAYER, BASF, DEGUSSA, DSM, J. MONTZ, KOCH-Glitsch, PRAXAIR, Saint Gobain NORPRO, SHELL, and SULZER Chemtech, for financial support of this project. Additional thanks to J. MONTZ, KOCH-Glitsch and SULZER Chemtech for donation of equipment used in this study.

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