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CHARACTERIZATION AND QUANTIFICATION OF THE QUALITY OF GAS FLOW DISTRIBUTIONS

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Abstract
Since the evaluation of the homogeneity of a distribution can be subdivided into two parts (magnitude and spatial distribution), a good key value describing the quality of the distribution has to consider both. The CoV value covers the effects of the fluctuation's magnitude, but any spatial information is lost. Therefore, a complementary key value (Coefficient of Distribution – CoD) was developed to consider both, magnitude and spatial distribution together. The new method is successfully applied to evaluate the vapour velocity distribution at the entrance to the packed bed above the vapour feed of an industrial distillation column with a large diameter.

Keywords: Distillation, Packed columns, Gas inlet devices, Maldistribution

1. Introduction
In packed distillation columns, the separation efficiency is influenced by many parameters such as e.g. the packing type, the liquid distribution at the top, and the gas distribution at the bottom of the column[1]. Especially in columns with large diameters, a homogeneous distribution of either phase over the cross section is challenging. While for the liquid distribution the use of the drip point density and wetting index as measures is quite standard, the characterization of the gas flow distribution at the bottom of the column is less clear[2]. A commonly used value to characterize the uniformity of the gas flow is the coefficient of variation (CoV = standard deviation / mean value, table 1).

Table 1. Equations for the calculation of the mean value, the standard deviation, and the CoV value for scalar distributions and 3D velocity distributions. c denotes the concentration of the tracer, $\vec{u}$ the velocity vector and $\left|\bar{u}_{FD}\right|$ the norm of the mean velocity component in flow direction.

Quantity	Scalar	3D velocity	Equation No.
Mean value	$\bar{c} = \frac{1}{n}\sum_i c_i$	$\bar{\vec{u}} = \frac{1}{n}\sum_i \vec{u}_i$	(1)
Standard deviation	$\sigma = \sqrt{\frac{1}{\lvert A\rvert}\int_A \left(c-\bar{c}\right)^2 dA}$	$\sigma = \sqrt{\frac{1}{\lvert A\rvert}\int_A \left(\vec{u}-\bar{\vec{u}}\right)^2 dA}$	(2)
Coefficient of Variation	$CoV = \frac{\sigma}{\bar{c}}$	$CoV = \frac{\sigma}{\left\lvert\bar{u}_{FD}\right\rvert}$	(3)

The CoV value is an averaged quantity over a region (area or space) and therefore not sensitive to spatial differences within the distributions. An example to highlight this is given in Figure 1. Two non-uniform velocity distributions with an identical CoV value are shown: large scale maldistribution (left) and small scale maldistribution (right). However, the large scale maldistribution will have a more severe effect on separation efficiency[3]. The failure of the CoV to describe both homogeneity and spatial distribution is a well known problem. This topic has been well investigated in the context of mixing[4,5]. This paper addresses the question how the CoV value can be modified to include spatial information as well.

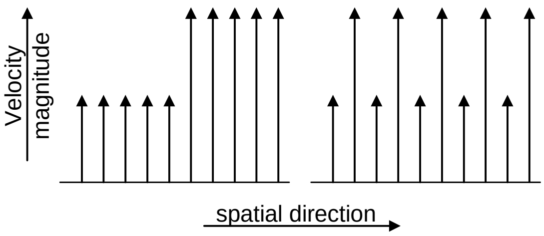


Figure 1. Sketch of two artificial velocity distributions: large scale (left) and small scale (right) maldistribution.

2. Theory

Figure 2 (taken from C.L.Tucker[6]: Figure 6 page 110) shows nine artificial situations differing in degree of mixing and spatial distribution of a scalar quantity. In the vertical direction the CoV value decreases, since the state becomes more mixed due to an equalization of the values (simulating a diffusive transport mechanism). The spatial distribution remains unchanged. The CoV in the first row is 100%, in the second row 60% and in the third row 20%. In the horizontal direction (from right to left) the length scale of the fluctuations decreases (simulating a distributive mixing processes), the CoV however remains constant.

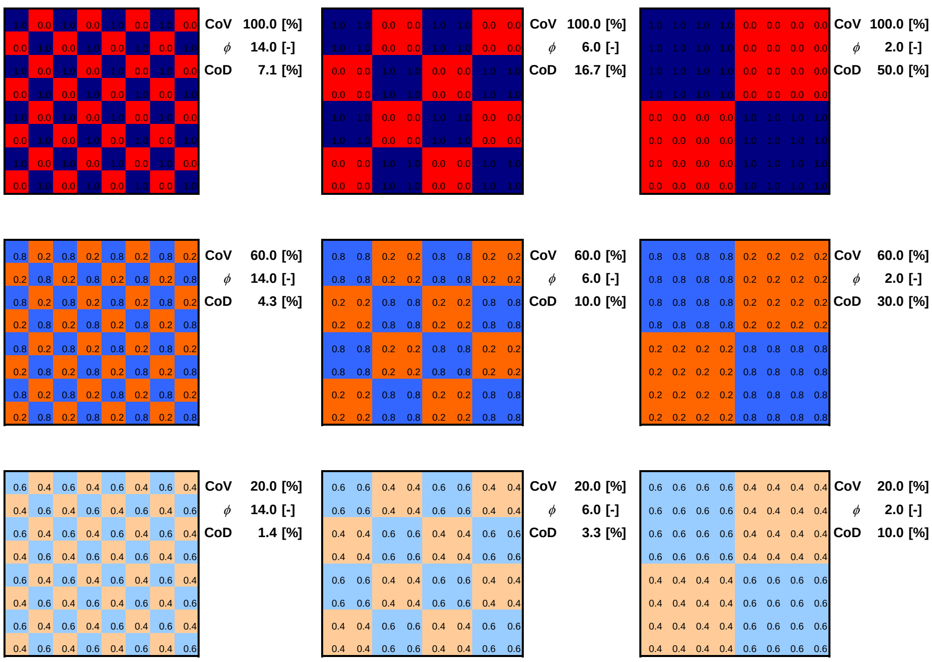


Figure 2. *Sketch of nine artificial tracer distributions. For each distribution the CoV, ϕ and CoD is given. Color scheme for the first row: dark blue: 1.0, red: 0.0; for the second row: blue: 0.8, orange 0.2; and for the third row: light blue: 0.6, light orange 0.4.*

It is clear that in this example the size of the squares serves the purpose of characterizing the length scale on which these fluctuations occur. The smaller the individual squares are, the better is the distribution. A good measure for the size of these squares is the length ℓ of the contact line between regions of different concentrations. In real cases, this contact line (or contact area) is of special interest, too, since diffusive and dispersive equalization strongly depends on it[7]. The length of contact line is made dimensionless by relating it to a characteristic length scale ℓ_{ref} e.g. the hydraulic diameter. Applied to the different distributions in figure 2 this dimensionless number ϕ is 2 (=16/8) for the right column, 6 (=48/8) for the middle and 14 (=112/8) for the left column (respective width of each square is 8). These values are independent of the degree of mixing or CoV. Here two key figures are available characterising different aspects of a scalar distribution - the commonly used CoV value to characterise the magnitude of the fluctuations and the ϕ value characterising the spatial distribution. The combination of both values leads intuitively to the definition of the **Coefficient of Distribution** CoD and allows comparing distributions of different mixing degrees and extents (diagonal directions within figure 2)

$$CoD = \frac{CoV}{\phi} \tag{4}$$

The value of the Coefficient of Distribution CoD (combining diffusive and distributive mixing effects) in figure 2 ranges from 50% for the worst mixing state down to approx. 2% for the best mixing state (bottom, left).

Extension to continuous systems

In artificial systems like figure 2, the length of the contact line is easy to find in contrast to real systems. From the measure theory it is known, that for a completely segregated system the integration of the norm of the gradient of a normalized value leads exactly to the length of the contact line[8] (between value 0 and value 1), but with increasing diffusive equalization it looses its significance. For practical reasons the norm will be made dimensionless by dividing through 2σ. The characteristic length scale ℓ_{ref} is obtained as the ratio of cross section and hydraulic diameter.

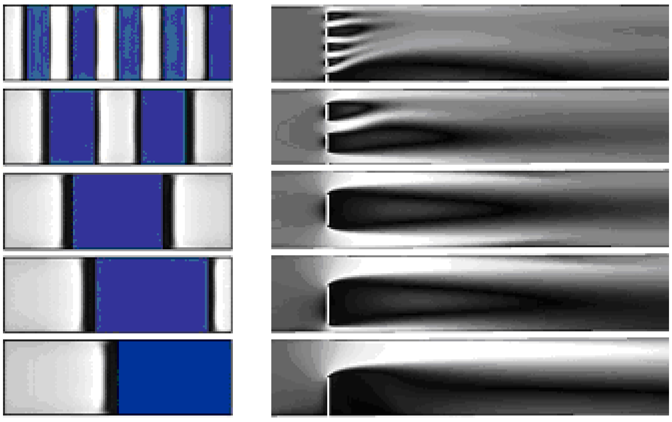
Extension to vector distributions

The generalization of the norm of the velocity gradient is straightforward. The obtained equations calculating the mean value, the standard deviation and the CoV value can be taken from table 1, the calculation of the vector norm and the length scale ϕ are shown in table 2.

Table 2. Equations for the calculation of the norm of the gradient and the length scale for scalar and 3D velocity distributions.

Quantity	Scalar	3D velocity	Equation No.
Norm of the Gradient	$\lVert\nabla c\rVert_2 = \sqrt{\sum_i (\partial_i c)^2}$	$\lVert\nabla \vec{u}\rVert_2 = \sqrt{\sum_i \sum_j (\partial_i u_j)^2}$	(5)
Length scale	$\phi = \frac{\ell}{\ell_{ref}} = \frac{d_h}{A} \frac{\int_A \lVert\nabla c\rVert_2 \, dA}{2\sigma}$	$\phi = \frac{\ell}{\ell_{ref}} = \frac{d_h}{A} \frac{\int_A \lVert\nabla \vec{u}\rVert_2 \, dA}{2\sigma}$	(6)

The applicability of the theory developed above is tested using the example of fluid flow through blinds (figure 3). The results were obtained from a CFD analysis using Reynolds-Averaged Navier-Stokes (RANS) equations together with a proper turbulence model to describe the fluid flow. The used numerical solver is Ansys CFX11. Five blinds of different size were investigated, ranging from very fine blinds (top) down to a very coarse one (bottom) which blocks one half of the cross section. Pictures on the left side show the flow distribution just behind the blinds; with a direct view in flow direction (white color denotes high velocities). The pictures on the right side show the corresponding top views. For the cross section right behind the blinds, the CoV values are given. It can be seen, that the CoV values have no real significance. The finest blind, which is expected to produce the best distribution, has the worst value. The coarsest blind is in the middle range. Figure 3 shows also the values of ϕ and CoD. The length scale ϕ increases from approx. 1.8 for the coarsest up to over 6 for the velocity distribution after the finest blind. Therefore the CoD changes as expected: The fine blind produces a velocity distribution which is more than three times better than the coarse one.



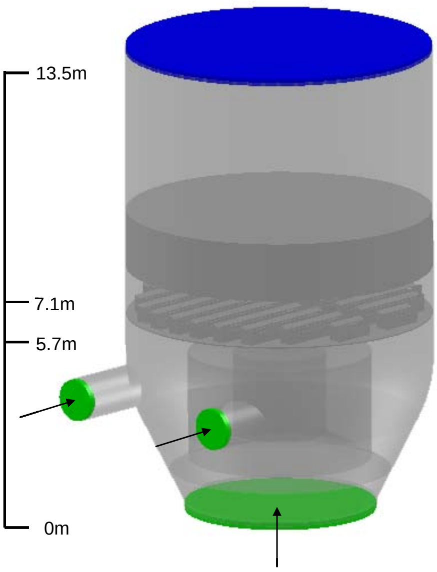
	CoV	ϕ	CoD
	125.115 [%]	6.1054	20.4926 [%]
	107.705 [%]	3.5806	30.0802 [%]
	106.713 [%]	2.54106	41.9954 [%]
	124.925 [%]	2.37738	52.5471 [%]
	116.816 [%]	1.75968	66.3847 [%]

Figure 3. *Velocity distributions on cross sections of flows through different blinds. Results gained from CFD. Left: Velocity distribution with the view in flow direction directly behind the blinds, right pictures show the top view (flow from left to right). The next three columns show the CoV value, the ϕ value and CoD for a cross section right behind the blinds.*

This simple example shows that the Coefficient of Distribution (CoD) is able to quantify different flows considering both magnitude and spatial distribution of the fluctuations. In the next chapter an investigation of a real industrial application will be done to prove the applicability to a complex situation.

3. Application to an industrial case

Since especially columns with large diameters develop maldistribution of the velocity over the cross section, such a case will be examined in the following. The design of vapour inlet systems to such columns is challenging. Whether the inlet is tangential or radial the velocity field that develops within the column is truly three dimensional. The CoD method is here applied to see whether a chimney tray can help to reduce the maldistribution induced by the feed system.



Column	Vacuum Tower	
Diameter	8.8	m
Column Temperature	385	°C
Column Pressure	13332	Pa
Pressure drop: Packing	439	Pa
Total side inlet flow rate	326	m^3/s
Flow from below	72	m^3/s
Vapor Density	0.261	kg/m^3
Average column F-Factor	3.34	$Pa^{0.5}$
Chimney Tray	10	rows

Figure 4. *Column configuration: Diameter of upper part: 8.8m, vapour is coming from below and through the 2 inlet nozzles. The chimney tray is shown separately (bottom right).*

The column has a diameter of 8.8m and an investigated height of 13.5m. The total vapour flow is approx. 400 m^3/s entering though three inlets, one from the bottom and two (with the main load) tangentially (figure 4). To ensure a homogeneous gas flow in front of the packing, a chimney tray is installed which has 10 rows of chimneys (figure 4: bottom, left). To quantify the effect of the chimney tray, an additional column identical in construction, but without chimney tray has also been calculated.

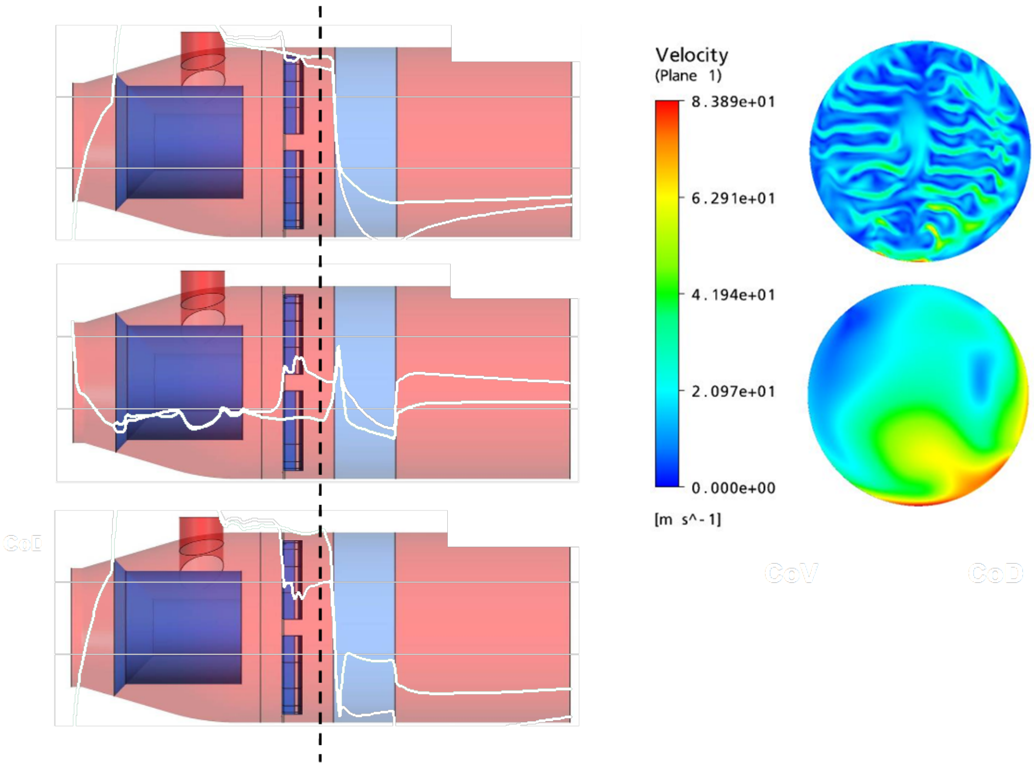


Figure 5 Axial distribution of CoV, ϕ and CoD

The velocity distributions in front of the packing (evaluation plane: 0.3m before the packing) can be seen in figure 5 (right). The upper one shows the velocity distribution for the vapour with the chimney tray, the lower one shows the one without a chimney tray, showing a big left/ right maldistribution. In contrast, with the chimney tray a much finer locally distributed velocity profile is obtained. Caused by the deflections of the chimney tray, the CoV value reaches high values of 250% and 360%. The length scale ϕ shows a difference of a factor of 4 comparing both situations; therefore, the generated scales with the chimney tray are 4 times smaller. The CoD values show a significant difference. The value for the flow through the chimney tray has a value below 10% and the flow without chimney tray has a value 5 times larger (more than 50%). Therefore the chimney tray has a significant positive influence, more than expected from the CoV alone[9].

4. Conclusions

A CFD investigation of a column with a very large diameter demonstrates the potential of the Coefficient of Distribution to characterize the gas flow distribution at the entrance to a packed bed. It combines the magnitude of the fluctuations with their dominant length scale. The CoD serves as a sound measure to calculate the influence of a non-uniform gas flow on the separation efficiency using standard maldistribution analysis. Further investigations will show what the maximum values of the CoD are to guarantee the expected efficiency of the packing.

Symbols

A	Area
c	concentration
d_h	hydraulic diameter
∂_i	i-th derivative
ϕ	ratio of ℓ and ℓ_{ref}
ℓ	length scale
ℓ_{ref}	characteristic length scale
σ	standard deviation
$\vec{u}$	velocity vector
u_{FD}	velocity component in main flow direction

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