CHEMICAL ENGINEERING RESEARCH AND DESIGN 89 (2011) 1392–1396

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

# 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 value of the coefficient of variation (CoV) 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 the packing type, the liquid distribution at the top, and the gas distribution at the bottom of the column (Edwards et al., 1999). A very concise overview of the earlier work done on gas flow distribution in packed columns can be found in Olujić et al. (2004). However, most of the work focussed on measuring the gas distribution rather than to give guidelines what quality may be acceptable. 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 (Spiegel, 2006). A commonly used value to characterize the uniformity of the gas flow is the coefficient of variation (CoV = standard deviation/mean value, Table 1).

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 illustrate this is given in Fig. 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 (Spiegel and Plüss, 1982). 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 (Dankwerts, 1952; Boss, 1986).

This paper addresses the question how the CoV value can be modified to include spatial information as well.

## 2. Development of a new concept

Fig. 2 (taken from Tucker and Rauwendaal, 1991: Fig. 6, p. 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 distributive mixing processes), the CoV however remains constant.

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

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Received 23 September 2010; Received in revised form 8 February 2011; Accepted 9 February 2011
0263-8762/$ – see front matter 
doi:10.1016/j.cherd.2011.02.022

**Nomenclature**

| | |
|---|---|
| A | area |
| c | concentration |
| $d_h$ | hydraulic diameter |
| $\partial_i$ | ith derivative |
| $\phi$ | ratio of $\ell$ and $\ell_{ref}$ |
| $\ell$ | length scale |
| $\ell_{ref}$ | characteristic length scale |
| $\sigma$ | standard deviation |
| $\vec{u}$ | velocity vector |
| $u_{FD}$ | velocity component in main flow direction |

squares is the length $\ell$ 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 (Kukukova et al., 2009). The length of contact line is made dimensionless by relating it to a characteristic length scale $\ell_{ref}$ e.g. the hydraulic diameter:

$$\phi = \frac{\ell}{\ell_{ref}} \tag{4}$$

Applied to the different distributions in Fig. 2 this dimensionless number $\phi$ 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 $\phi$ 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 Fig. 2)

$$\mathrm{CoD} = \frac{\mathrm{CoV}}{\phi} \tag{5}$$

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

### 2.1. *Extension to continuous systems*

In artificial systems like Fig. 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 (Bothe et al., 2006) (between value 0 and value 1). Applied to real systems, the distribution will be made dimensionless and being scaled by a division with $2\sigma$. The characteristic length scale $\ell_{ref}$ is obtained as the ratio of cross section and hydraulic diameter.

A restriction for the calculation of the length of the contact line appears for systems with a massive increasing diffusive equalization. There it looses its significance, but the achieved values get smaller, so the key value of the CoD is conservative.

### 2.2. *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 $\phi$ are shown in Table 2.

## 3. Application

### 3.1. *Application to a simple 3D flow*

The applicability of the theory developed above is tested using the example of a gas flow through openings (Fig. 3). The

**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 $|\bar{u}_{FD}|$ the absolute value of the mean velocity component in flow direction.**

| Quantity | Scalar | 3D velocity | |
|---|---|---|---|
| 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 | $\sigma = \sqrt{\frac{1}{\lvert A\rvert}\int_A (c-\bar{c})^2 dA}$ | $\sigma = \sqrt{\frac{1}{\lvert A\rvert}\int_A (\vec{u}-\bar{\vec{u}})^2\, dA}$ | (2) |
| Coefficient of variation | $\mathrm{CoV} = \frac{\sigma}{\bar{c}}$ | $\mathrm{CoV} = \frac{\sigma}{\lvert\bar{u}_{FD}\rvert}$ | (3) |

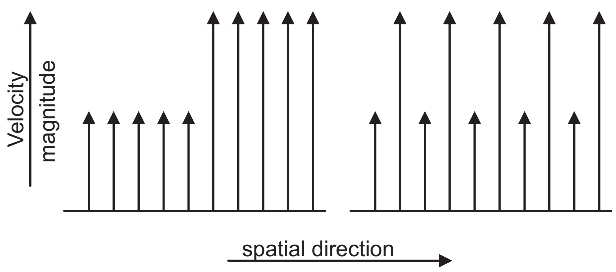


**Fig. 1 – Sketch of two artificial velocity distributions: large scale (left) and small scale (right) maldistribution.**