

**METHOD FOR ESTIMATION OF THE GAS PHASE MALDISTRIBUTION
IN PACKED BED COLUMNS**

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Abstract

A detailed analysis of the gas phase maldistribution in packed bed column is carried out based on the experimental data for some random and structured packing at different packing heights. The maldistribution is expressed by the maldistribution factor, calculated from the radial velocity profiles sampled by different number of measuring points. It is shown that by increasing the number of measuring points over the column cross-section the gas maldistribution factor increases gradually but after a definite number of points it does not change more - a "plateau" is reached. This number of the sampling points, respectively the size of the sample area determines the scale of the registered maldistribution – large or small one. This way the different scale maldistributions and the zones where they appear could be identified.

Key words: *Packed columns, Gas maldistribution, Large/small scale maldistribution*

1. INTRODUCTION

One of the main problems that deteriorate packed beds' performance is the non-uniformity of the gas or liquid phases' distribution in the column bulk. The sources of the non-uniformity depend on: the type of the gas or liquid inlet device; gas or liquid velocities in the apparatus and the height and type of the packing layer – random or structured [1].

The main criterion enabling the quantity measure of the gas flow non-uniformity in the column is the maldistribution factor [1-3]. Usually, it is the mean square deviation of the local gas flow velocities from their mean value, measured for an arbitrary column cross-section. Depending on the area of column cross-section, on which they are observed, different types of gas flow non-uniformity are estimated through this value.

Two types of the maldistribution effects of gas flows can be observed in packed-bed columns – large and small-scale. The large-scale maldistributions occupied the area of column cross-section larger than area of some packing particles and are generated by:

- The type, geometrical configuration and the location of gas distribution device mounted at the entrance of the apparatus (Fig.1- a,c);
- The presence of column wall or another zones with higher porosity and different equivalent diameter (Fig.1, a,b);
- The variation of the velocities of the wall and bulk zones with the increasing in packing layer height in the apparatus;

The small-scale maldistributions (Fig.1, d) are manifested in the scale of few packing particles and are expressed with different values of local velocities radially. The packing layer itself in the apparatus generates small-scale effects. Every type of packing represents a redistributor of the gas flow and spread its own disturbance in him.

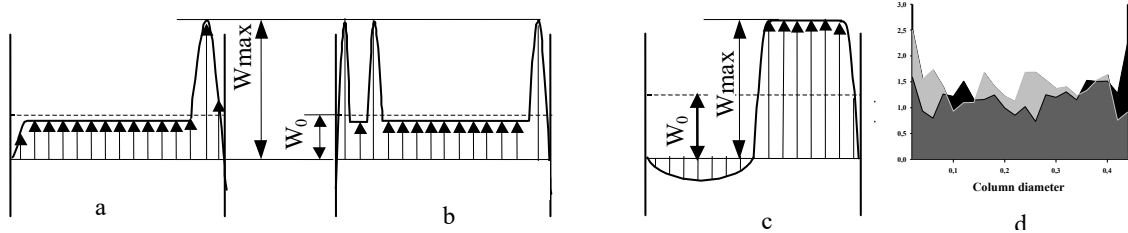


Fig.1. Various types of gas velocity profiles –a,b,c [4] and d.

Since the velocity profiles can be quite different, (Fig.1, a-d), the estimation for their maldistribution has to include as the local stream velocities, as well the section of the cross-section area of the column, which they are occupied, e.g., their “weight” in the maldistribution factor. The maldistribution factor M_f represents such integral valuation answering to above-mentioned inquiries:

$$M_f = \sqrt{\frac{1}{F_0} \int_{F_0} \left(\frac{w - w_0}{w_0} \right)^2 dF}, \quad w_0 = \frac{1}{F_0} \int_{F_0} w dF \quad (1)$$

where w, w_0, F, F_0 are the current and mean gas velocity and the current and whole cross-section area of the apparatus, with dimensions (m/s) and (m²), respectively.

Depending on the various methods to measuring the velocity profile, the next variants to calculate M_f are differentiated:

- Measurement in cells with area F_i

$$M_f = \sqrt{\frac{1}{F_0} \sum_{i=1,N} F_i \left(\frac{w_i - w_0}{w_0} \right)^2}, \quad w_0 = \frac{1}{F_0} \sum_{i=1,N} F_i \cdot w_i \quad (2)$$

where F_i is the area of each cell, (m²), $i=1 \div N$, N is the cell numbers. If the area of all such cells F_i is equal, (Fig.2, left), the most often used formulae for maldistribution factor obtains:

$$M_f = \sqrt{\frac{1}{N} \sum_{i=1,N} \left(\frac{w_i - w_0}{w_0} \right)^2}, \quad w_0 = \frac{1}{N} \sum_{i=1,N} w_i \quad (3)$$

- Measurement in two perpendicular diameters

If the velocity profile measurement is carried out in two perpendicular diameters (Fig.2, right), the column cross-section may be divided virtually to some concentric ring-shaped segments [5]. In every of these segments four points can be placed. In such case, to determine correctly the maldistribution factor the weight of each measuring point must be accounted by the corresponding segment area F_i in Eq.(2).

In both cases the local and mean gas velocities after the some packing layer in the apparatus can be measured with thermoanemometer or Pitot tube, etc. Then one may use the Eqns. (1)÷(3) to calculate the maldistribution factor and estimate large and small maldistributions in the column.

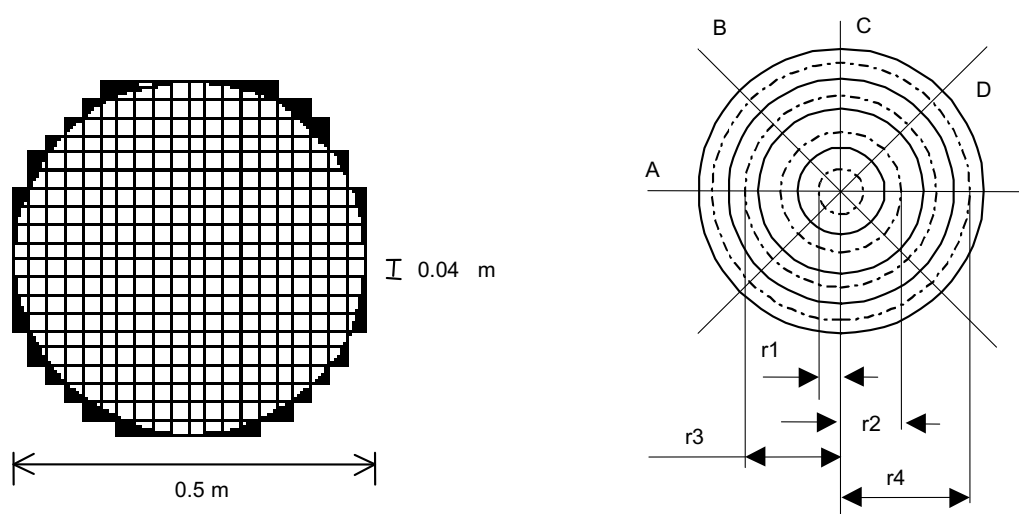


Fig.2 Sketches of measuring point's location over the column cross-section; left – in rectangular cells 0.04 x 0.04 m, and right – in concentric segments.

After this short introduction in basic terms of gas maldistribution measurement in packed bed columns the following questions arise:

- Can the gas maldistribution factor be estimated correctly using two-diameter measurement?
- How the gas maldistribution factor does depend on the number of measurement cells (the sampling size respectively)?
- How the different scale gas maldistribution effects are registered depending on the number of measurement cells (their size respectively)?
- How the gas maldistribution factor is changed in wall and bulk zone separately with the increasing in packing layer height in the apparatus?

2. EXPERIMENTAL DATA FOR GAS MALDISTRIBUTION IN PACKED BEDS

The set of experimental data for gas velocities measurements from [1, 6-8] is used to check the answers of above-mentioned questions. Measurements have been taken in a packed bed column with diameter $D=0.47\text{m}$ at various packing heights $H_i(\text{m})$ in the absence of liquid phase, using the thermoanemometer KURZ 440 (USA). Its precision and reproducibility is $\pm 2\%$ of the apparatus scale.

Four types of modern high-effective random packings have been considered - Raschig Super-Ring Plastic (RSRP 2"), Raschig Super-Ring Metal (RSRM 2"), Raschig Super-Ring Metal (RSRM 3"), and Intalox Metal Tower Packing (IMTP 25"). Two structured ("Honey-comb", Holpack) and one conventional random (Pall rings) packing are used also.

Two different measuring procedures have been applied (Fig. 2, left and right) to receive the gas velocity profiles along column cross-section after certain packing layer height for these packings. Local gas velocities have been measured in 44 points along two perpendicular column diameters (RSRM 2, RSRP 2, IMTP 25) at $H=0.8$ m. For packing Pall rings and Holpack gas velocity measurements have been made in 20 points along two perpendicular diameters, at $H=0.8$ m and $H=0.268$ m, respectively. For packings RSRP 2, RSRM 2, RSRM 3" and IMTP 25 velocity profile is measured also in 112 rectangular cells at $H=0.8$ m and in the case of Honey-comb in 184 rectangular cells, at $H=1.5$ m. Cell dimensions was 0.04×0.04 m.

3. METHOD FOR ESTIMATION OF THE INFLUENCE OF NUMBER AND SIZE OF MEASURING POINTS ON THE VALUE OF MALDISTRIBUTION FACTOR

As is well seen, the values of M_f calculated with Eq. (2) and (3) for two different measurement procedures (Figs. 3 to 5) coincide quite well with difference of 0.7 % and 1 % for the RSRP 2 and RSRM 2, respectively. Also the zones of high porosity are well visible – this is so called "gas wall flow" located near the column wall (Figs.3 and 4), where local velocities exceed the mean one. Now, it is clear that the measurements of local gas velocities in 44 points are enough to register the large-scale maldistribution effects for these packings. For IMTP 25" (Fig.5) the difference between M_f 's is 1.1%, but here the wall flow is lower because of the difference between IMTP packing size (25 mm) and the measuring cell area (0.04 m). As is well known, the smaller size packings like IMTP 25 smooth gas inlet maldistributions better than bigger one, which is confirm by lower value of its M_f .

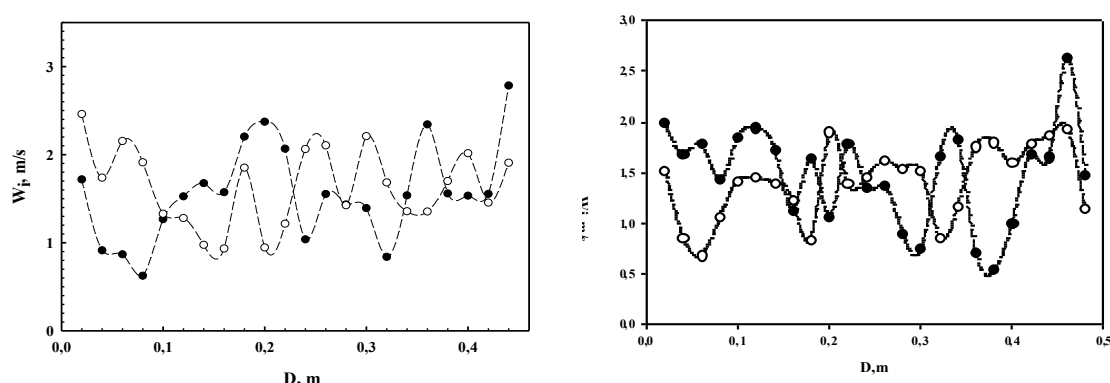


Fig. 3. Profiles of local velocities, measured in at two perpendicular diameters D in 44 points (11 concentric segments) at $H=0.8$ m for the packing RSRP 2, $M_f=0.305$ (left) and the same for packing RSRM 2, $M_f=0.32$ (right).

In our previous work preliminary analyses were done [8], to answer the question about the influence of cell size on the value of M_f . The idea was to start from certain number of measuring cells and

reduces gradually the number of cells, increasing at the same time the area of new, bigger area cell. Reduction was done with alternation of cells integration direction. This procedure was done for both two types of measurement techniques and is illustrated here on some of the packings. Every two neighbour cells are integrated to one with twice-bigger area and arithmetical mean velocity. In each reduction the maldistribution factor is calculated – Eq.(3). For the case of Eq.(2), each two consecutive segments are integrated. The cell numbers reduction (cell areas increasing, respectively) is done, starting from:

- 112 (random packings RSRP 2, IMTP 25);
- 184 (structured packing “Honey-comb”);
- 44 (random packings RSRP 2, IMTP 25);
- 20 (random packing Pall rings 50 mm).

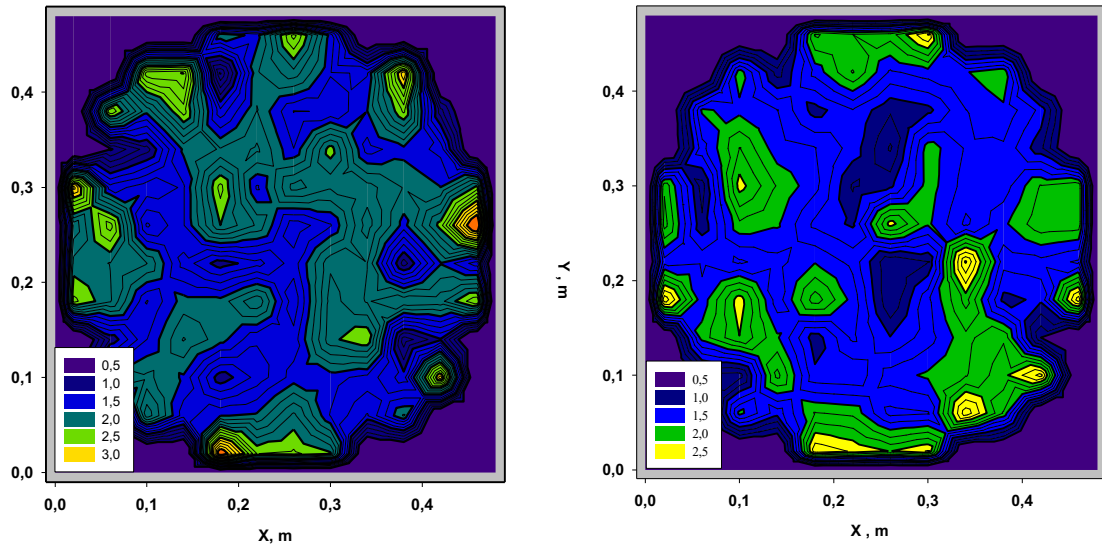


Fig. 4. 3-D contour maps of local velocities, measured in 112 equal cells at $H=0.8$ m for packing RSRP 2, $Mf=0.312$ (left), and for packing RSRM 2, $Mf=0.31$ (right).

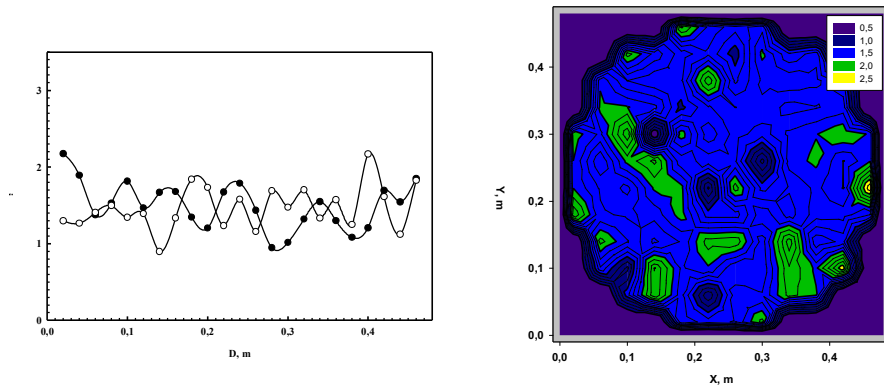


Fig.5. Velocity profiles measured in 44 points (11 concentric segments) at 2 perpendicular diameters at $H=0.8$ m, for packing IMTP 25, $Mf=0.215$ (left) and in 112 equal cells, $Mf=0.226$ (right).

The change in values of M_f after reduction is characterized with reaching a “plateau”, for both measuring techniques. The presence of this “plateau” is a proof that the value of maldistribution factor stops to depend on the number of measuring cells. As it is well seen from the Figs. 6 and 7 for small packing size – IMTP 25 mm, about a 20 cells are needed to register a large scale maldistribution in M_f , accordingly 44 points for packing RSRP 2. Registering of small-scale maldistributions for IMTP 25 needs more than 112 cells. This packing creates small-scale maldistributions, which cannot be registered fully for choused cell area. A larger number of smaller area cells are needed to account small-scale effects (the second “plateau” will be appear) in M_f for this case.

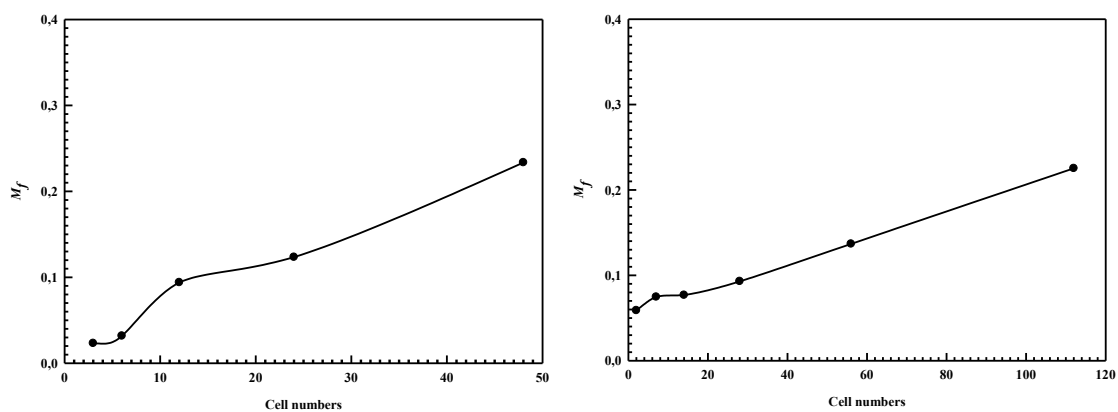


Fig. 6. Cell numbers reductions for packing IMTP 25 at H=0.8 m, measured in 2 perpendicular diameters (left) and measured in 112 equal cells (right).

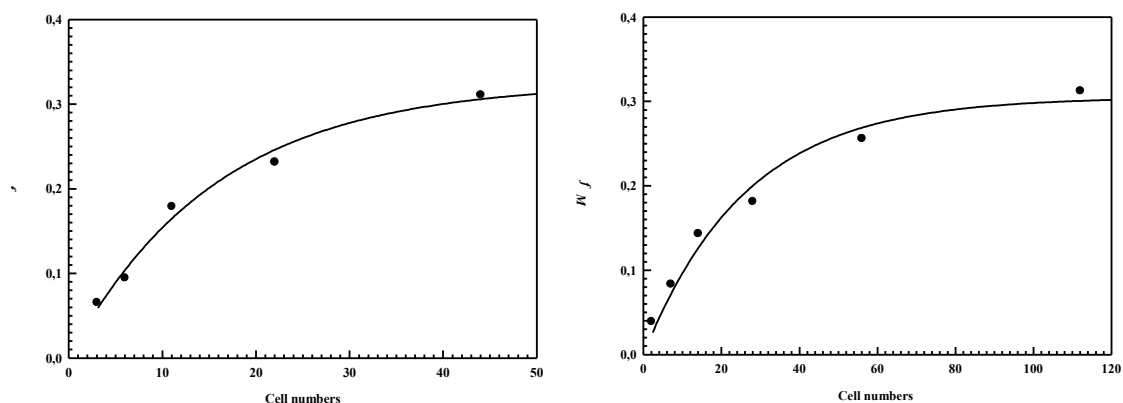


Fig. 7. Cell numbers reduction for the packing RSRP 2 at H=0.8 m, measured in 2 perpendicular diameters (left) and measured in 112 equal cells (right).

The “plateau” exists also at the next Fig. 8 for random packing Pall rings and two structured packings Honey-comb and Holpack. Here less than 20 points are needed to account large scale maldistribution

in M_f , because of more ordered packing structure for these packings, which equalizing the gas flow after the packing layer height [1,8]. Values of M_f for packings Pall rings, Honey-comb and Holpack, are lower or comparable with modern ones. Modern random packings like RSRP 2 and IMTP 25 create very low pressure drop, which is due to their “open” structure. At the same time, this kind of packing structure generates more local variations in gas flow velocities after the packing layer, creating wall zone with higher porosity for RSRP 2 and RSRM 2 near the column wall (large scale effects). Then they are can equalize the initial large scale maldistributions at shorter packing layers, but the larger number of measuring cells are needed to account the small scale one in M_f completely especially for small size packings.

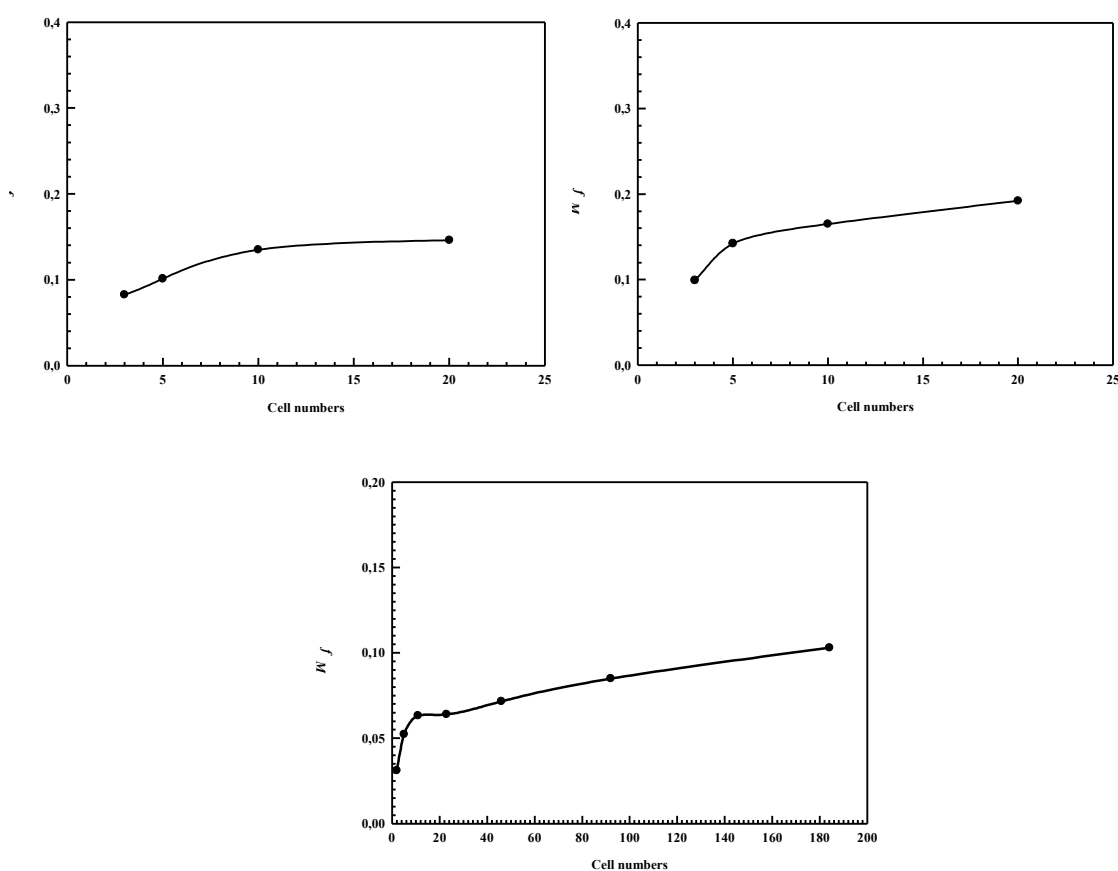


Fig. 8. Cell numbers reduction for random packing Pall rings at $H=0.8$ m, measured in 2 perpendicular diameters (up, left); for structured packing Holpack at $H=0.27$ m measured in 2 perpendicular diameters (up, right); for structured packing “Honey-comb” at $H=1.5$ m measured in 184 equal cells (down, centre).

4. INFLUENCE OF WALL AND BULK ZONES IN CALCULATION OF GAS MALDISTRIBUTION FACTOR DURING THE INCREASING OF PACKING LAYER HEIGHT

When the packing layer height increases it is evident that M_f will change too. In the most of the cases large scale maldistribution effects disappear with the increasing the packed height, but there are packings, for which further increase of the M_f value is observed [1]. One probable explanation is the presence of two zones in the packed layer with different porosity – bulk and wall zone. Their impact in calculation of M_f varies for different type of packings with increasing of packing height. Calculating M_f by Eq. (3) starting from the center of bulk zone (N=4 rectangular cells) and adding more and more cells along the column diameter while include all 112 cells, it is clear than values of mean velocity and M_f will change. This assumption is tested on velocity profiles in 112 cells for packings RSRP 2 and RSRM 3 at H=0.8 m and for IMTP 25 at H=0.8 and 1.3 m.

For the case of IMTP 25 at H=0.8 and H=1.3 m the observed dependence between number of cells N in Eq. (3) on the corresponded to this N value of M_f can be seen at Fig. 9. After N=50 cells (this is roughly the area of bulk zone) values of M_f remains constant (about 0.22) and that of mean velocity slightly increase from 1.22 m/s at N=4 to 1.35 m/s at N=112 for packing layer H=0.8m. At H=1.3 m M_f changed from 0.35 at N=4 to 0.28 at N=112, and mean velocity grows from 1 to 1.36 m/s. Decreasing in maldistribution factor can be explained with small deviations of local velocities from mean one in the bulk zone (Fig. 5). As is well seen the slight increasing in mean velocity is due to supplement of cells, formed the wall zone, i.e after first 50-60 cells (bulk zone). Nevertheless, the value of M_f in 112 points increases with increasing the packed layer height from 0.8 to 1.3 m. Here the ‘weight’ of gas velocities in the bulk zone dominated in calculation of M_f because smaller packing size create higher pressure drop practically at whole cross-section and does not predispose creation of visible wall zone with higher porosity.

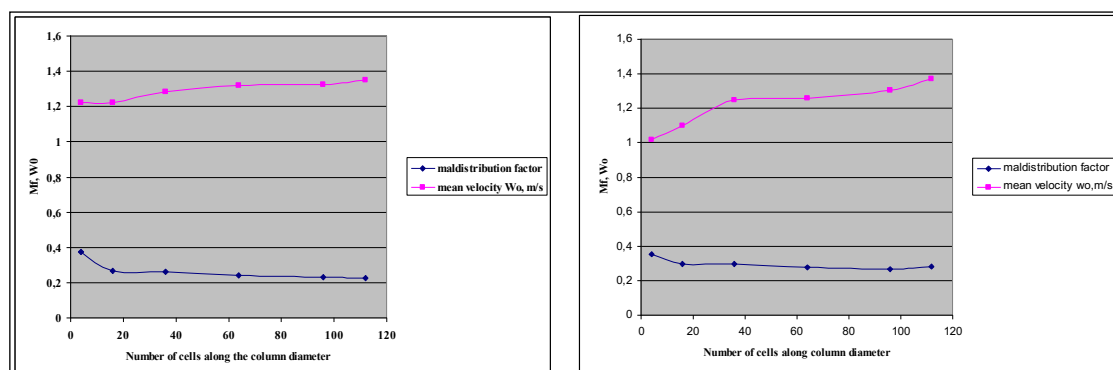


Fig.9. Dependence between number of cells N in Eq.(3) on the values of mean velocity and maldistribution factor for IMTP 25 at H=0.8 (left) and at H=1.3 (right)

In the case of larger packing sizes the situation is opposite. In Fig.10 increasing of both mean velocity and M_f 's value at $H=0.8$ m is due to the existence of well-visible wall zone (see also Fig. 4, left), formed roughly after first 40 cells. For packing RSRP 2 mean velocity at $N=36$ is $w_0=1.59$ m/s and $M_f=0.20$; at $N=112$ $w_0=1.62$ m/s and $M_f=0.31$. For RSRM 3" at $N=36$ $w_0=1.40$ m/s and $M_f=0.27$; at $N=112$ we have $w_0=1.64$ m/s and $M_f=0.31$. Increasing in the packing size generated wall zone with higher porosity for identical type of packing, velocity measurement conditions and equation for M_f calculation.

5. CONCLUSIONS

After detailed analyses on the considered experimental data for gas velocity profiles measured in different manners at various packed heights, the methods for estimation of gas maldistribution factor are proposed. They checked the influence of number and size of sampling cells in calculation of M_f both for some random and structured packing, as well as the optimal number of cells needed to account large and small scale maldistributions at the column cross-section. Two types of zones – bulk and wall zone are identified for various types of packings, which have a different impact in calculation of M_f with increasing the packed layer height. The following conclusions are taken out:

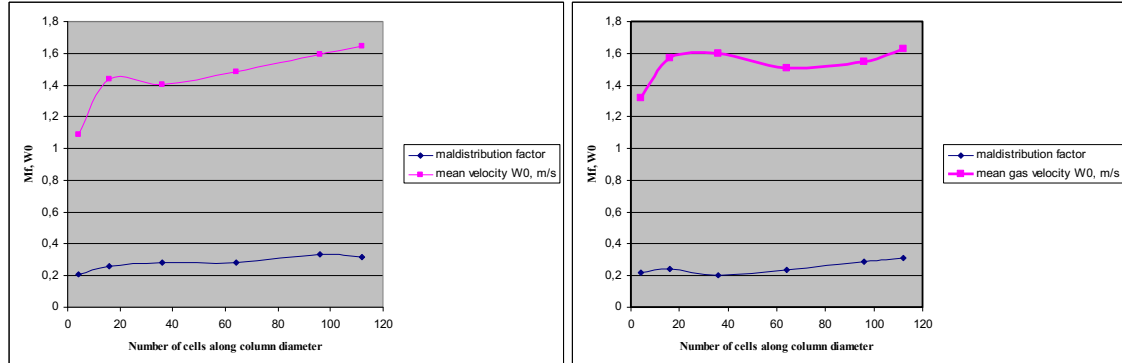


Fig.10. Dependence between number of cells N in Eq.(3) on the values of mean velocity and maldistribution factor for RSRM 3 (left) and for RSRP 2 (right) at $H=0.8$ m.

- With increasing the number of sampling (measuring cells) M_f increases gradually while a “plateau” is attained. This “plateau” determines the optimal number of cells after which maldistribution factor remains constant for given packing height.
- The large-scale maldistribution effects can be accounted correctly in the maldistribution factor by measuring the gas velocities in two perpendicular diameters.
- The degree of accounting the small-scale maldistribution effects increases at increasing the cell numbers. For some kind of packings the number of cells is not enough and it is recommend decreasing the area of measurement cell, in conformity with packing size.

- Packing height increasing generate higher pressure drop in the whole column and changes the values of mean velocities in bulk and wall zone along the column diameter. Larger packing size create well visible wall zone with higher porosity and higher local and mean velocities which results to increasing in .

The further work will be focused on a quantitative assessment of the impact of the wall zone on for different type of packings and on applicable measures for restriction of the gas wall flow in order to ensure better performance of the packing bed.

ACKNOWLEDGEMENTS

This study has been carried out with the financial support of the Grant scheme № BG051PO001-3.3.04/30 /28.08.2009 under the Operational Program “Human Resources Development” 2007-2013, co-financed by European Social Fund of European Community.

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