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Air isothermal flow through packed beds

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Abstract

The experimental study of the air flow through a packed bed has been done under working conditions close to those used in the case of drying. The measuring of the local velocities has been done for long beds ($L/D > 1$), high dimensions pellets ($d > 5$ mm) and in the domain of intermediate flow (Re = 100–400). To correlate the obtained results there has been used as dimensionless velocity the ratio between the local velocity of the air inside the bed and the local velocity of the air in the empty column. The deduced equations have shown that the velocities distribution is influenced by the Re number, the D/d ratio and the L/d ratio.

Keywords: Packed bed; Air flow through packed beds

1. Introduction

The passing of a gaseous phase through a packed bed has been much studied as it takes place in catalytic reactions, in gas–solid chemical reactions and in the drying, adsorption and thermal transfer processes. The distribution of the fluid local velocity in the intergranular space, the pressure loss and the resistance coefficients are influenced by the flow regime, the internal structure of the packed bed, the dimensions and the shape of the pellets as well as the dimensions and the shape of the packed bed.

The geometry of the free spaces from the inside of the packed bed has been experimentally studied for the monodisperse [1–7] and polydisperse packed beds [4,8–12], respectively, being demonstrated the fact that the profile of the local porosity on a normal direction to the wall has the appearance of some damped oscillations whose amplitude can be considered as null at the distance of 3–6 diameters from the wall. Debbas and Rumpf [4] have shown that the results are not reproducible because the layer porosity depends on its forming way. In the syntheses made by Ziolkowska and Ziolkowski [13], Foumeny et al. [14], Stanek [15] and Achenbach [8], the conclusions have been that the average porosity of a monodisperse cylindrical packed bed depends on the pellets shape and on the D/d and L/D ratios.

The flow approach through the granular bed has been preferably done for a restricted domain of variation for the Reynolds number. In the case of the ideal systems with a uniform spatial structure, there have been developed cellular models which gave satisfactory results in the domain of small [16–19] and intermediary Reynolds numbers [20–23], respectively. In the domain of the turbulent flow, there exist numerous experimental studies in which the various computation relations of the resistance coefficients and of the distribution of the gaseous phase velocity [24–33] have been established.

In the real system, the experimental measurements [34] have shown that the local velocity is influenced by the distribution of the local porosity while the wall effect and the entry effect are important. The Reynolds critical value varies between 10 and 300 [13], according to the pellets shape and dimensions.

To render the porosity effect on the velocity distribution, there have been drawn up zonal models [35–42] which are based on the hypothesis that the cylindrical packed bed is made up of two or three concentric zones, each one having another average porosity and a total displacement flow. The mathematical relations deduced for the radial distribution of the velocity include as parameters the D/d ratio, the Re number or the average porosity of the respective zone.

This experimental study tries to established the velocity distribution at the flow of the air through a

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cylindrical granular bed under working conditions close to those encountered during drying. The measurements have been also done in the intermediate flow domain (Re = 100–400), for long beds ($L/D > 1$), and high dimensions pellets ($d > 5$ mm). In the equations deduced for the radial distribution of the velocity there appear as parameters the L/d ratio, a fact which makes them useful in the elaboration of the model for the drying of the granular beds penetrated by gaseous thermal agents.

2. Experimental technique

The measuring of the local velocity has been done on the installation presented in Fig. 1 with the help of a thermoanemometer. To determine the velocity there has been provided a breaking of the bed having a 20 mm height in which there has been placed the probe of the apparatus which can be set in any point of the column section. The local velocity of the air are measured at the outlet from the lower bed while the presence of an upper bed, with the same structure, diminishes the disturbance of the velocity distribution.

To form the packed bed there have been used two types of bodies: glass spheres with a 5.5 mm diameter and porous spheres made up of ceramic material with a 18 mm diameter. Two different columns have been employed, one with a 150 mm diameter, the other one with 100 mm diameter. The length of the bed, considered between the lower sieve and the measuring device, had three values in the case of the first column (150, 385, 680 mm) and two values in the case of the second column (230, 680 mm). The length of the upper bed, set above the measuring zone, has been kept constant at 200 mm value.

The air flow rate varied in the case of the 150 mm column between 20 and 65 m^3/h while in the case of 100 mm column between 9 and 27 m^3/h. The measurements have been done at the environment temperature, the values ranging between 14°C and 23°C.

The local velocities have been measured on half of the column section. In the 150 mm diameter column there have been measured the local velocities in 300 points for each established bed and air flow rate while in

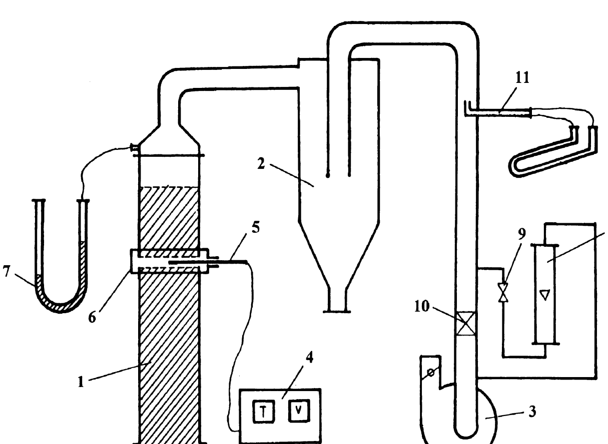


Fig. 1. Schematic of the experimental installation: 1 – granular bed; 2 – cyclone; 3 – fan; 4 – thermoanemometer; 5 – probe with thermistor; 6 – sealing and positioning device of the probe; 7 – differential gauge; 8 – rotameter; 9, 10 – supply adjustment valve; 11 – Pitot–Prandtle tube.

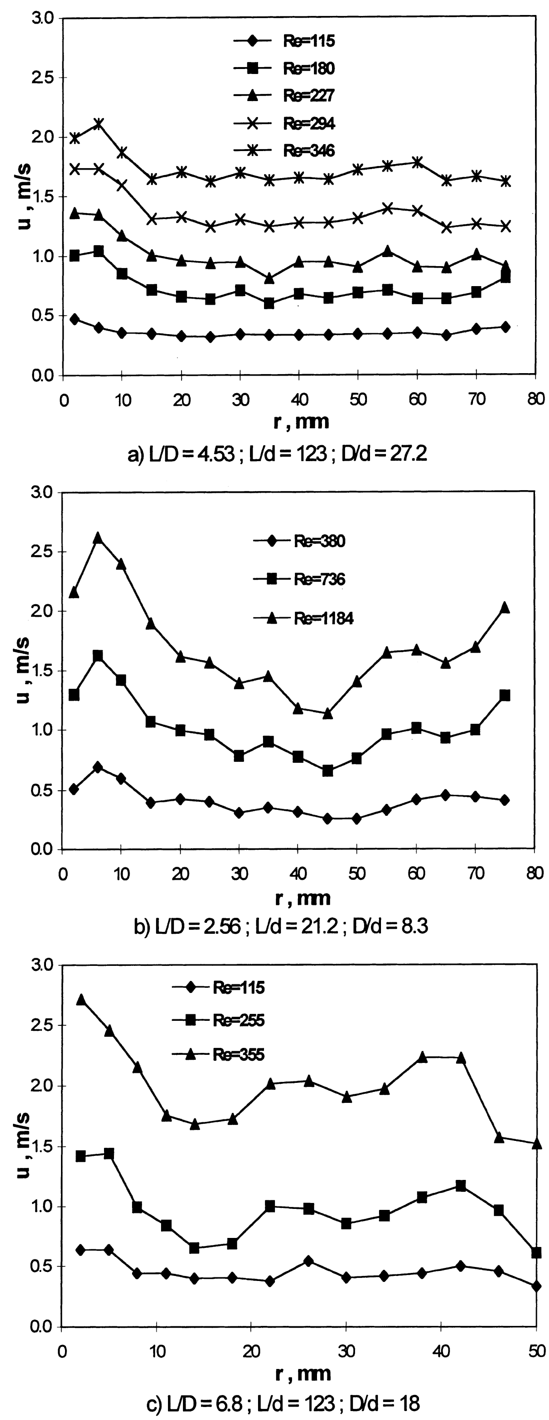


Fig. 2. Radial distribution of the local velocity.

the 100 mm diameter column the local velocities have been measured in 280 points.

As the structure of the packed bed influences vary much the values of the gas local velocities, a great importance has been given to the bed formation. The spherical pellets have been poured on portions in the column and after each pouring the column has been shaken to remove the abnormal dimensions empty spaces. It has been necessary to repeat more times the forming operation of the granular bed so that the distribution of the porosity should be at random and preferential zones of the gas flowing should not appear.

3. Experimental results

The following factors have been taken into account as influencing the velocity distribution at the isothermal flow of a gaseous phase through a packed bed: the bed length, the bed diameter, the pellets diameter, the gas flow rate. As the absolute values of the beds and pellets dimensions do not allow a satisfactory correlation of the results, they have been considered under the form of the following geometrical criteria: L/D, L/d and D/d. The Reynolds criterion has been computed with the most used relation in the case of the flow through packed beds

$$\mathrm{Re} = \frac{\bar{u}\, d}{\nu}. \tag{1}$$

The measuring of the local velocities has been done for eight beds characterized by different values of the three geometrical ratios. In the case of each bed, there have been used gas flow rates with different values, so that the total number of experiments should be 25. The measured values of the local velocity in 11 of the accomplished experiments are presented in Fig. 2. Each point represents the average of the local velocity values, measured on half a circle set at a certain distance from the column wall.

On analyzing the measurements results, one can note the dependence of the local velocity upon the radial position and the values of the Reynolds number. The experimental data confirm the existence of a zone adjacent to the wall, mentioned in all the studies regarding this domain [1–8,13,34–42], in which the local velocity increases from zero, reaches a maximum value after which begins to decrease. This characteristic variation of the velocity in the peripheric zone of the bed is explained by arrangement of pellets in the vicinity of the solid boundary, a fact which leads to the increase of the local porosity. The magnitude of the zone depends upon the factors under study and there has not been possible the establishing of a direct cor-

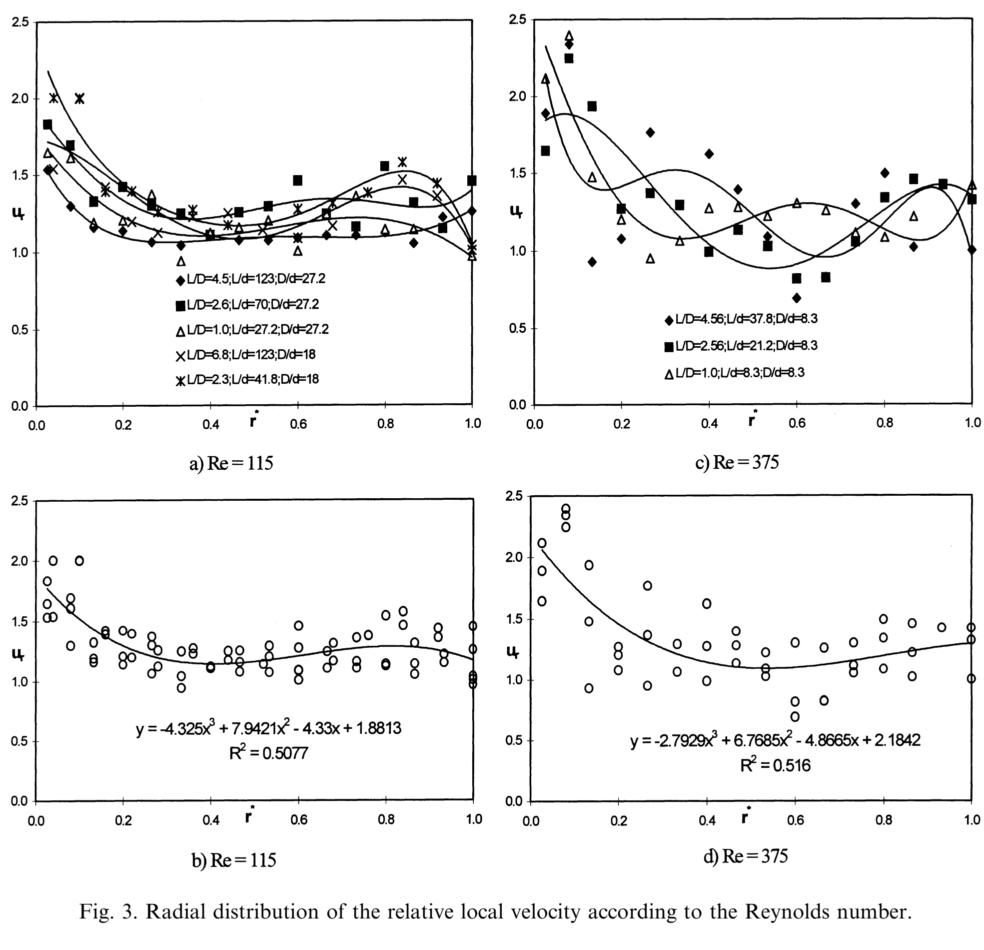


Fig. 3. Radial distribution of the relative local velocity according to the Reynolds number.

relation between the zone dimensions and the values of the other parameters. From the experimental distributions of the local velocity there results that the annular peripheric zone has a width of 5–15% from the bed radius, the higher values being registered for small values of the D/d ratio. In the central zone of the bed, the radial variation of the velocity presents maximum and minimum values of small amplitude, a fact which could justify the models elaborated by some researchers [37,40–42] who consider that a total displacement flow takes place here.

To compare the experimental data, we have used as dimensionless coordinates the local relative velocity, i.e. the ratio between the local velocity and the superficial velocity:

$$u_r = \frac{u}{\bar{u}} \tag{2}$$

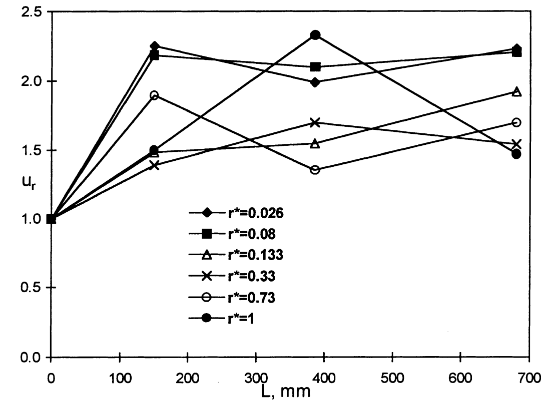
and the dimensionless radial coordinate which represents the ratio between the distance from the column wall and the bed radius

$$r^* = \frac{R - r}{R}. \tag{3}$$

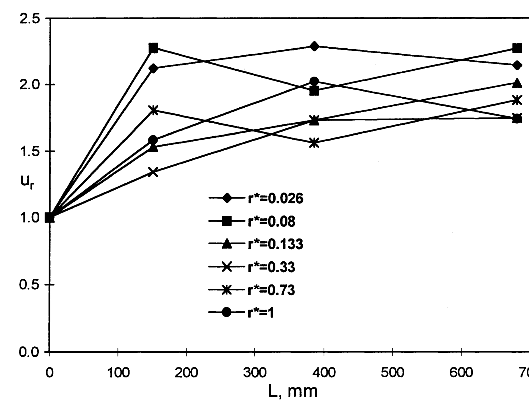
The great number of accomplished measurements made necessary a statistic processing of the experimental data. To correlate the data, various types of regressions have been tried, the highest values of the correlation indices being obtained in the case of the polynomial regression. The various distribution of velocity in the two mentioned zones made impossible the establishing of an equation for describing the velocity variation on the entire section of the column. That is why the statistic modeling has been done by leaving aside the sudden increase of velocity in the near vicinity of the wall on a distance representing 2–4% from the bed radius.

On considering the very marked dependence of the velocities distribution on the Reynolds number values, the results for its first two values are shown in Fig. 3. The regression equation under the form of a fifth degree polynom has been established for each experiment, the corresponding curves being presented in Fig. 3(a) and (c). The same data have been correlated in Fig. 3(b) and (d) on considering that there would exist a velocity variation domain depending only on the Reynolds number irrespective of the geometrical ratios values. The regression equation which correlates the data from the entire domain is a third degree polynom. The existence of the two zones in which the local velocities vary differently is much more emphasized and the amplitude of the minimum and maximum values is much diminished in the central zone.

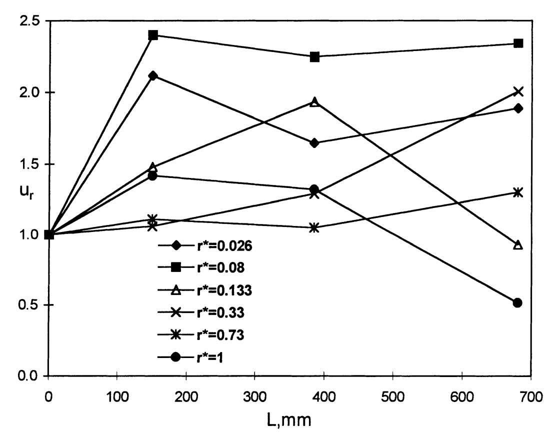
The dependence of the local velocity on the axial position is rendered in Fig. 4 for the 150 mm diameter column. It is difficult to establish the velocity axial distribution as the measurements have been done only for three beds of various lengths. However, one can estimate that in the case of high beds ($L/D > 1$), the radial profile of the velocity is the same, no matter what the axial position is. The zone adjacent to the wall is extremely well emphasized in this case as well.



a) Re = 227 ; D/d = 27.2



b) Re = 330 ; D/d = 27.2

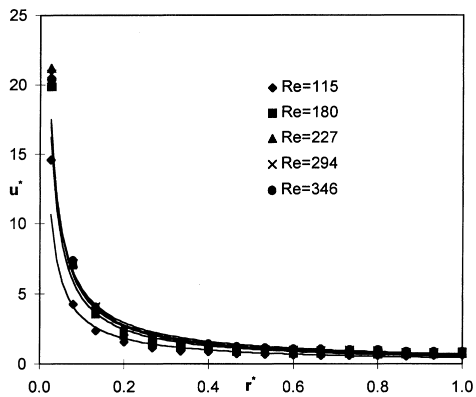


c) Re = 380 ; D/d = 8.3

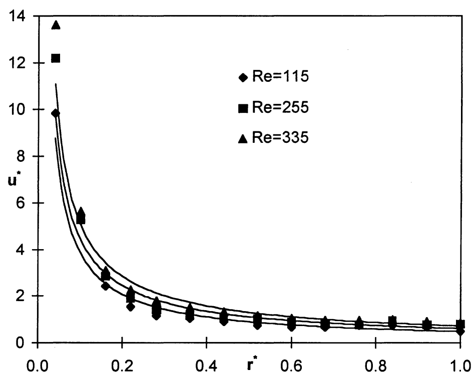
Fig. 4. Axial distribution of the relative local velocity.

4. The modeling of the isothermal flow through the packed bed

On using for the experimental data representation the local relative velocity, i.e. the most usual way of rendering the results, there has been noticed that it is not possible the deduction of some general models which should describe the distribution of the gaseous phase velocities according to the factors which influence the



a) L/D = 4.53 ; L/d = 123 ; D/d = 27.2



b) L/D = 6.8 ; L/d = 123 ; D/d = 18

Fig. 5. Radial distribution of the relative velocity.

flow through the intergranular space. That is why we suggest the ratio between the local velocity and the local superficial velocity as dimensionless variable

$$u^* = \frac{u}{u_1}, \tag{4}$$

which we called relative velocity. The local superficial velocity is the local velocity of the gas in empty column. As the Reynolds number computed for the column without the filling material with the relation

$$\mathrm{Re_f} = \frac{\overline{u}\, D}{\nu} \tag{5}$$

has values ranging between 2000 and 9400, one can admit that the profile of the local superficial velocity is parabolic

$$u_1 = 2\overline{u}\left[1 - (1 - r^*)^2\right]. \tag{6}$$

Under the new coordinates, the experimental results from Fig. 2(a) and (c) are given in Fig. 5(a) and (b). As one can see, the dimensionless distribution of velocities has got the same aspect which is maintained for all the accomplished experiments. The introduced variable exchange has led to the results uniformness, a fact which allowed us to suggest for the velocities distribution a relatively simple variation function of the following form

$$u^* = \frac{a}{(r^*)^b}. \tag{7}$$

The a and b coefficients from Eq. (7) have been estimated for each of the 25 accomplished experiments and they are presented in Table 1. Their values are de-

Table 1
Values of the a and b coefficients

	Re	$\mathrm{Re_f}$	u (m/s)	L/d	D/d	a	b
1	115	3128	0.310	123	27.2	0.443	0.878
2	180	4895	0.480	123	27.2	0.546	0.935
3	227	6174	0.610	123	27.2	0.595	0.933
4	294	7997	0.790	123	27.2	0.643	0.908
5	346	9411	0.930	123	27.2	0.720	0.873
6	116	3155	0.310	70	27.2	0.513	0.902
7	224	6093	0.597	70	27.2	0.645	0.858
8	318	8650	0.850	70	27.2	0.668	0.870
9	115	3128	0.310	27.2	27.2	0.469	0.899
10	230	6256	0.620	27.2	27.2	0.639	0.879
11	325	8840	0.910	27.2	27.2	0.640	0.872
12	376	3120	0.310	37.8	8.3	0.365	1.082
13	737	6117	0.610	37.8	8.3	0.540	1.053
14	1158	9611	0.940	37.8	8.3	0.504	1.081
15	380	3154	0.310	21.2	8.3	0.447	0.973
16	736	6109	0.610	21.2	8.3	0.585	0.954
17	1184	9847	0.980	21.2	8.3	0.609	0.953
18	374	3104	0.310	8.3	8.3	0.482	0.951
19	768	6374	0.636	8.3	8.3	0.637	0.965
20	115	2070	0.318	123	18	0.485	0.899
21	255	4590	0.707	123	18	0.614	0.859
22	335	6030	0.920	123	18	0.725	0.847
23	116	2088	0.318	41.8	18	0.920	0.920
24	258	4644	0.707	41.8	18	0.927	0.927
25	355	6390	0.972	41.8	18	0.902	0.902

pending on all studied factors and it has been difficult to deduce the equations which correlate best these values without getting to complicated mathematical functions.

For the coefficient a it has been established a linear equation of the following form

$$a = 0.363 + 2.6236 \cdot 10^{-5}\mathrm{Re_f} + 3.184 \cdot 10^{-3}\frac{D}{d}, \quad (8)$$

which has a correlation coefficient of 0.704 and for the coefficient b a linear equation of the following form

$$b = 1.03486 - 1.000335 \cdot 10^{-4}\frac{L}{d} - 5.352 \cdot 10^{-3}\frac{D}{d} \quad (9)$$

with a correlation coefficient of 0.722.

The mathematical model elaborated on the basis of the experimental study of the velocities distribution at the air flow by a packed bed includes the influence of the bed dimensions, the pellets diameter and the gas flow rate. The values calculated with Eq. (7) of the relative velocity and the measured values of the relative velocity

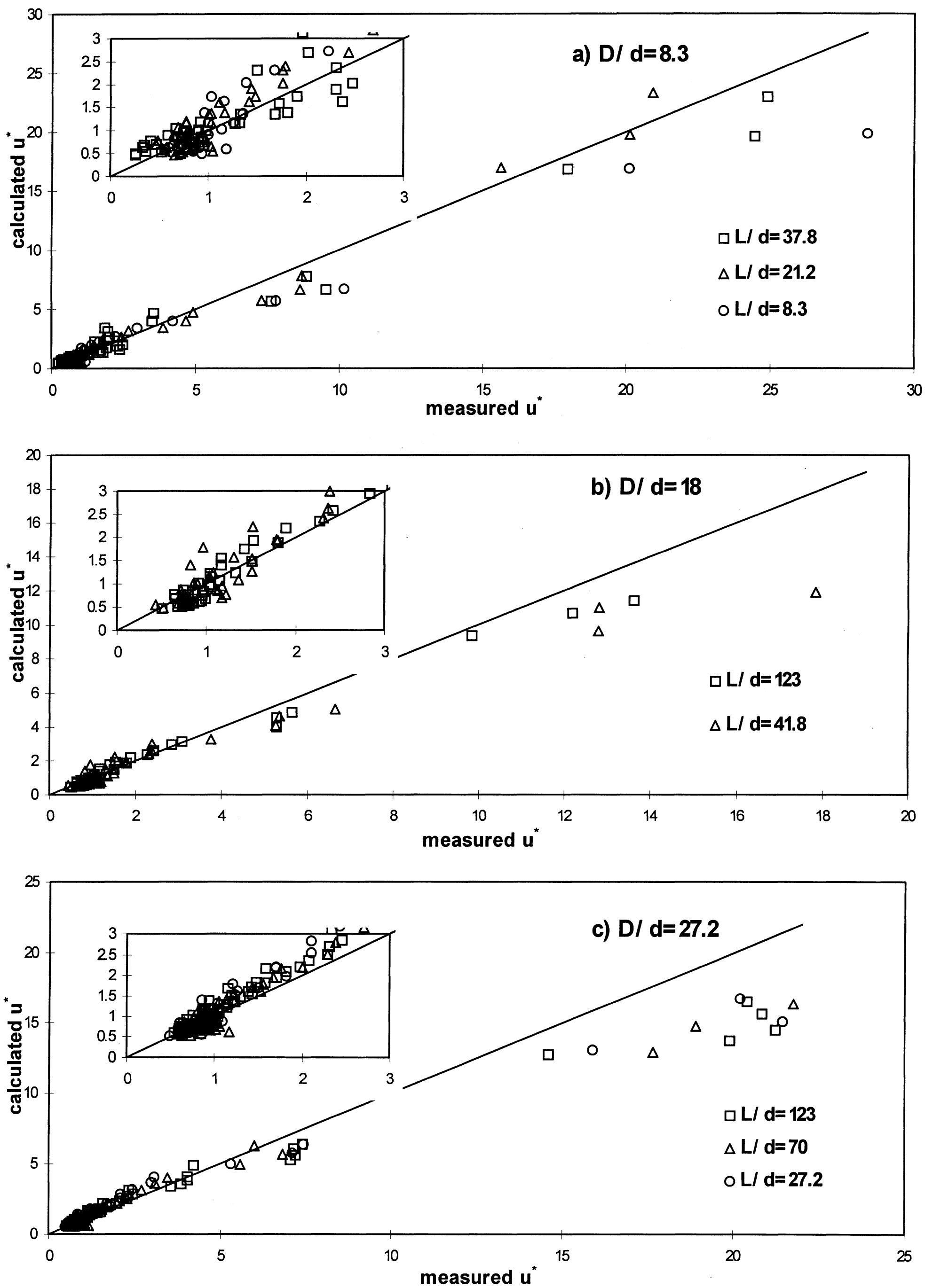


Fig. 6. Checking of the mathematical model.

are presented comparatively in Fig. 6. The three diagrams (a–c) include all the accomplished measurements, the data being grouped according to the *D*/*d* ratio.

Very high values of the relative velocity are registered in the zone adjacent to the wall, here appearing as well the highest deviations of the computed values as compared with the measured ones. The higher the *D*/*d* ratio is, the higher the deviations are. The agreement between the suggested mathematical model and the experimental data are satisfactory in the central zone of the bed.

5. Conclusions

The experimental study of the air flow through a packed bed has been accomplished for high dimensions pellets, long beds and intermediate flow regime. The measuring of the local velocities has been done in the inside of the bed, in a free zone with a 20 mm height. The upper bed with the same geometric structure has the role of reducing the modification of the velocity field.

The obtained results attest both the existence of the annular zone adjacent to the wall in which the velocity registered the maximum value and the dependence of the local velocity in the rest of the bed on the value of the Reynolds number, on the pellets dimensions and on the bed dimensions.

The best correlation of the experimental data has been obtained by using as dimensionless velocity the ratio between the local velocity of the air inside the bed and the local velocity of the air in the empty column. The deduced equations show that the velocities distribution is influenced by the Re number and *D*/*d* and *L*/*d* ratios.

Nomenclature

a	coefficient in Eq. (7), dimensionless
b	coefficient in Eq. (7), dimensionless
d	pellets diameter, m
D	bed diameter, m
L	bed length, m
r	radial coordinate, m
r^*	dimensionless radial coordinate $(= (R-r)/(R))$, dimensionless
R	bed radius, m
Re	Reynolds number $(= (\overline{u}\,d)/(v))$, dimensionless
$\mathrm{Re_f}$	Reynolds number $(= (\overline{u}\,D)/(v))$, dimensionless
u	velocity, m/s
$\overline{u}$	superficial average velocity, m/s
u_l	superficial local velocity, m/s
u_r	dimensionless local velocity $(= u/\overline{u})$, dimensionless
u^*	dimensionless velocity $(= u/u_l)$, dimensionless
n	kinematic viscosity, m^2/s

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