DISTRIBUTION OF SOLID PARTICLES IN A MIXED VESSEL

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The aim of our research was to study the axial, radial and tangential solid phase concentration profiles in a mixed vessel. The conductivity method was used for the concentration measurement. We accomplished the measurement in eleven points in five heights above the vessel bottom. The points were situated on three vertical planes passing through the vessel axis and on five values of radii. It was determined by means of statistic test of variance if it was possible to measure the concentration only in one point in each distance from the vessel bottom and neglect the radial and tangential concentration differences.

There is often a demand for homogeneous distribution of solid phase particles in suspension in chemical and food industries. One of the ways to reach it is to use a mechanical agitator. In that case it is necessary to determine the agitator speed and power consumption for the process. To determine the agitator speed whereby the optimum solid phase distribution in the vessel is reached is therefore significant from the economical point of view.

The simpliest method used for the solid phase concentration measurement is the samples taking method[1-3]. Checked samples are taken from various places of the mixed vessel and the solid phase content is determined. However, it is not possible to recommend this method for the measurement of the concentration of large particles which are not well withdrawn by the liquid to the samples taking points.

The radiometric method uses the dependence of solid phase concentration on the radiation intensity corresponding to the passage of the radiation beams through the clear liquid or a suspension. The basic description of this method is given in[4,5]. Various applications of this method use α, β, γ or X-ray beams in open or covered sources. The advantage consists especially in the possibility to install a measuring system out of the vessel and carry out the measurement through a non-transparent wall. The disadvantage is a relatively high price of the system and great demands on the work security.

The other method to carry out the solid phase concentration measurement is a conductivity one, worked out by Pešan[6] and used e.g. in refs[1,7,8,11,12]. It is based on the suspension conductivity changes measurement in dependence on the quantity

of present solid phase particles. Therefore it is advantageous to use it for suspensions of conductive liquid and non-conductive solid particles. It is possible to trace instantaneous conductivity changes in form of analogue signal changes. Reference[6] brings the survey of published relations of $\gamma_b = f(c, \gamma_p, \gamma_f)$ type gained theoretically or empirically. The comparison of all used methods is presented in[9].

EXPERIMENTAL

It was used the conductivity measurement method for concentration measuring during our research. The conductivity probe consisted of two electrodes, Fig. 1. The outside electrode is formed by six 20 mm long stainless steel parallel wires placed in the corners of regular hexagon. Wires are conductively connected with a 22 mm diameter ring joined to a main carrying tube. The inside stainless steel electrode is conductively connected to the main tube. Neutral conductor is connected to the inside electrode. This probe was used for conductivity measurement e.g. in[11,12].

We have used the bridge connexion of counting circuit, Fig. 2. The conductivity probe was in one branch of the bridge, in other branch there was a resistance decade. The measuring equipment was a tensometric device TDA 3. It was necessary to gauge the probe before measuring by means of the resistance decade. No. 2 which was placed in the bridge instead of the probe. The resistance of the decade No. 2 which had a value R_0 when counting circuit balanced (zero value of a mV-meter on a tensometric device) was increased by steps of ΔR and the corresponding displacement of the recorder finger was recorded.

There must be a zero value adjusted on a mV-meter before each measurement with a conductivity probe takes place. During the measurement the mV-meter output is recorded by a recorder which displacement δ is corresponding to a relative resistance $R_0/(R_0 + \Delta R)$ or its reciprocal value — relative suspension conductivity G_p. Then it is possible to calculate the local value of solid phase concentration by the relation $c_v = 2(G_p - 1)/(2G_p + 1)$.

It was used a flat-bottomed cylindrical glass vessel with inside diameter D and height of liquid surface H, where $D = H = 300$ mm. The vessel was equipped by 4 radial baffles whose width $b = 0{\cdot}1D$. Turbine with six flat, inclined blades was used for mixing. Blade inclination angle was 45°. The impeller diameter was $d = 100$ mm ($D/d = 3$) and the H_2/d ratio was 0·5 — see Fig. 3. The liquid was forced towards the vessel bottom along the impeller shaft and raised along the vessel wall. Water (20°C) with a small amount of salt (to rise the conductivity) and glass balls were used for experiments. Glass balls of two diameter $d_p = 1\,343$ μm and 419 μm in two average concentrations $c_v = 2{\cdot}5$ and 10% were used. Their density was 2 630 kg m^{-3}.

The dislocation of points wherein the local solid phase concentration was measured is shown in Fig. 4. The points are marked by numbers 1—11. Because of the assumption of flow symmetry we have measured only in 1/8 of the vessel volume. Concentration was measured in 5 distances from the vessel bottom — 40, 100, 160, 220, 280 mm — in each of 11 points. Total of measuring points was then 54 (it was not possible to measure in point 4 in distance 40 mm from the bottom because the impeller is situated here).

RESULTS

The results are shown in form of axial concentration profiles in Figs 5—8 for 4 combinations of solid particles diameter and average concentration. Each line is marked by the number of measuring point according to Fig. 4.

1. $d_p = 1\,343\ \mu m\,, \quad \bar{c}_v = 2{\cdot}5\%$

By 300 r.p. m. the majority of solid phase particles lay inert on the bottom. Their layer is shoved to the vessel wall where its height is 30 mm. Axial concentration

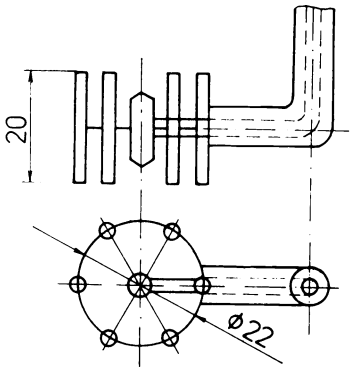

FIG. 1
Conductivity probe

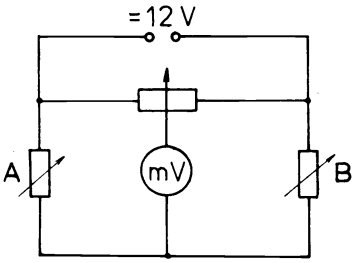

FIG. 2
Bridge connexion of counting circuit: A resistance decade, B conductivity probe (resistance decade No. 2)

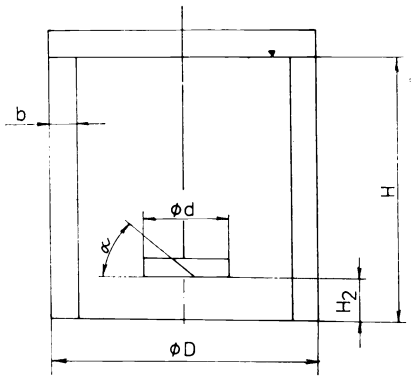

FIG. 3
Mixed vessel

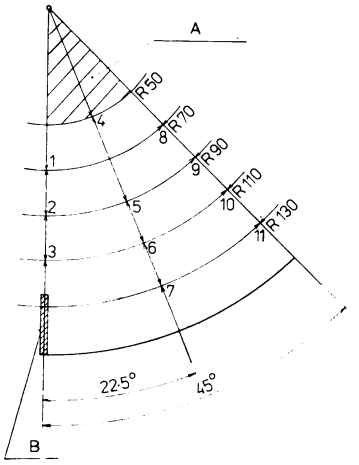

FIG. 4
Conductivity probe positions: A impeller region, B baffle

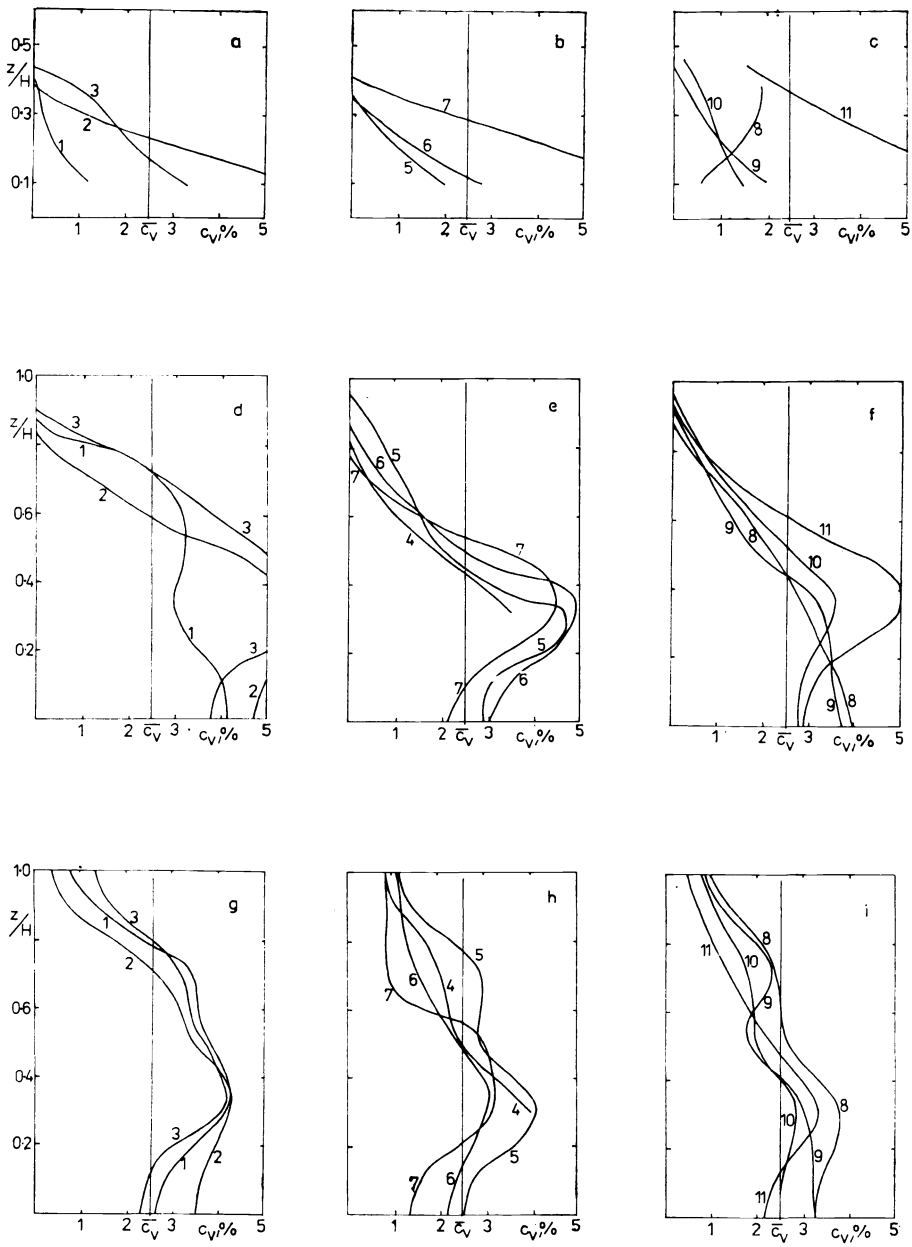

FIG. 5

Axial concentration profiles $d_p = 1\,343\ \mu m$, $\bar{c}_v = 2{\cdot}5\%$

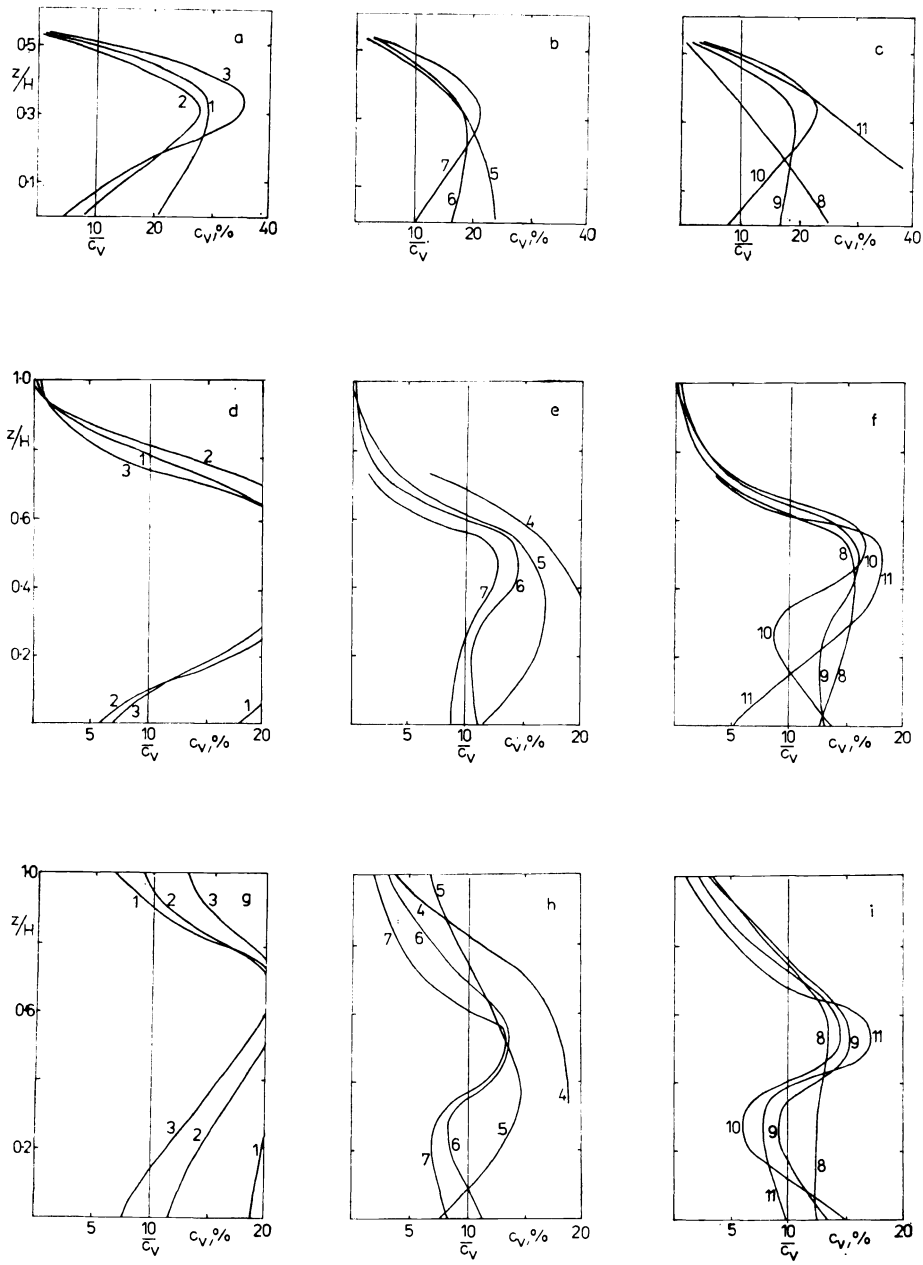

FIG. 6

Axial concentration profiles $d_p = 1\,343\ \mu m$, $\bar{c}_v = 10\%$

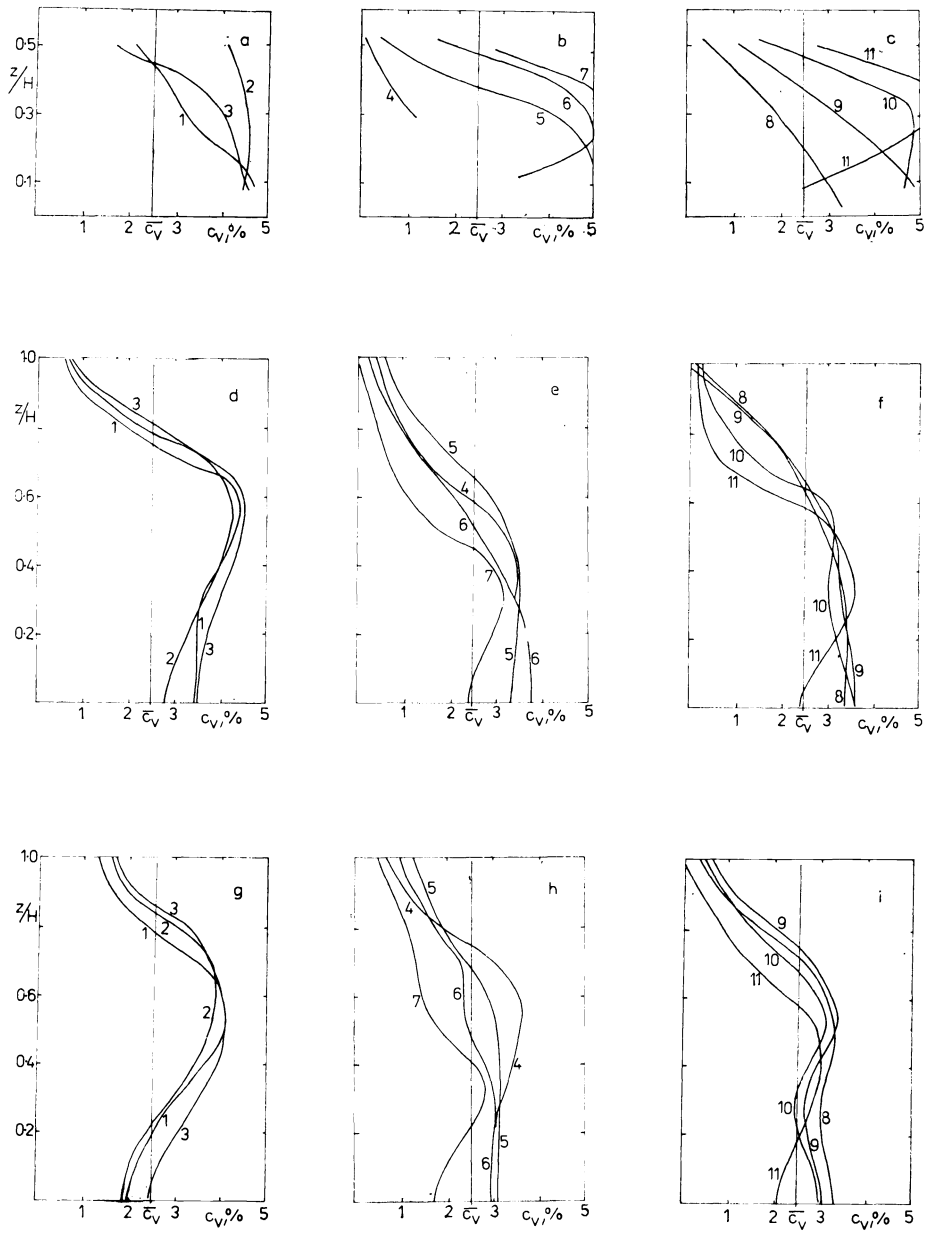

FIG. 7

Axial concentration profiles $d_p = 419$ μm, $\bar{c}_v = 2{\cdot}5\%$

profiles are on Fig. 5a–c. Floating balls reach up to 2/5 of the liquid column only. The highest solid phase concentration is near the wall (points 7, 11) where particles are carried up.

By 500 r.p.m. (Fig. 5d–f) particles are approximately in the so called "suspension state" (the state when solid particles become fully suspended). The highest concentration is around 110 mm above the vessel bottom where the great cloud of floating particles is kept. Concentration grows slightly from the vessel axis towards its wall. Concentration is higher in points facing the baffle than in the region between two baffles. Suspension is still considerably unhomogeneous and none of the particles reaches the liquid surface.

By 700 r.p.m. (Fig. 5g–i) a better suspension homogeneity is reached and particles are carried up to the liquid surface. The highest concentration is 90 mm above the bottom. Radial concentration profile is negligible in comparison with the tangential one – concentration is higher in points facing the baffle than between the baffles. Concentration is only slightly higher near the wall than near the vessel axis.

2. $d_p = 1\,343\ \mu m\,, \quad \bar{c}_v = 10\%$

By 600 r.p.m. (Fig. 6a–c) particles are not in the suspension state. Around 15% of particles lay on the vessel bottom and their layer is 15 mm high in the corner by the wall. The energy of floating particles is low and particles do not mount higher than to 3/5 of the liquid column height. The highest concentration is in 1/3 of the column height. Concentration grows here towards the vessel wall where particles are showed up. There is an opposite situation near the bottom – concentration is lower by the wall (except of point 11).

By 800 r.p.m. particles reach the suspension state, but the suspension homogeneity is not good, although some particles flow to the liquid surface, Fig. 6d–f. The highest solid phase concentration is again in the baffle plane. The densest cloud of particles is floating in 1/2 of the liquid column height. Concerning the radial concentration profile, solid phase concentration falls towards the vessel wall in the lower half of the vessel and is approximately constant in all the points in its upper half. Tangential concentration profile is more significant when compared with the radial one.

By 1 000 r.p.m. a better suspension homogeneity is reached (Fig. 6g–i). The highest concentration is approximately in 3/5 of the liquid column height. The tangential concentration profile remains more significant when compared with the radial one due to high concentration in the baffle plane. Concentration falls again towards the vessel wall in the lower half of the vessel. Strong vortices are rising in the upper half and by 1100 r.p.m. the aeration on the liquid surface occurs.

3. $d_p = 419\ \mu m\,, \quad \bar{c}_v = 2{\cdot}5\%$

By 300 r.p.m. around 10% of particles lay inert on the bottom and their layer is 12 mm high in the wall corner. Great number of solid particles are forced up along the vessel wall (high concentration in points 7, 11) but are not rising higher then to 1/3 of the liquid column height. The fact of great concentration increase in the baffle plane is not so significant as in the case of large particles, the radial concentration profile is consequently more visible then the tangential one. Axial concentration profiles in points 7 and 11 are interesting – high concentration values in upper part of floating cloud and strong drop close to the bottom – Fig. 7a–c.

By 450 r.p.m. particles are in the suspension state. They reach the liquid surface and the suspension homogeneity is much better than in the case of large particles

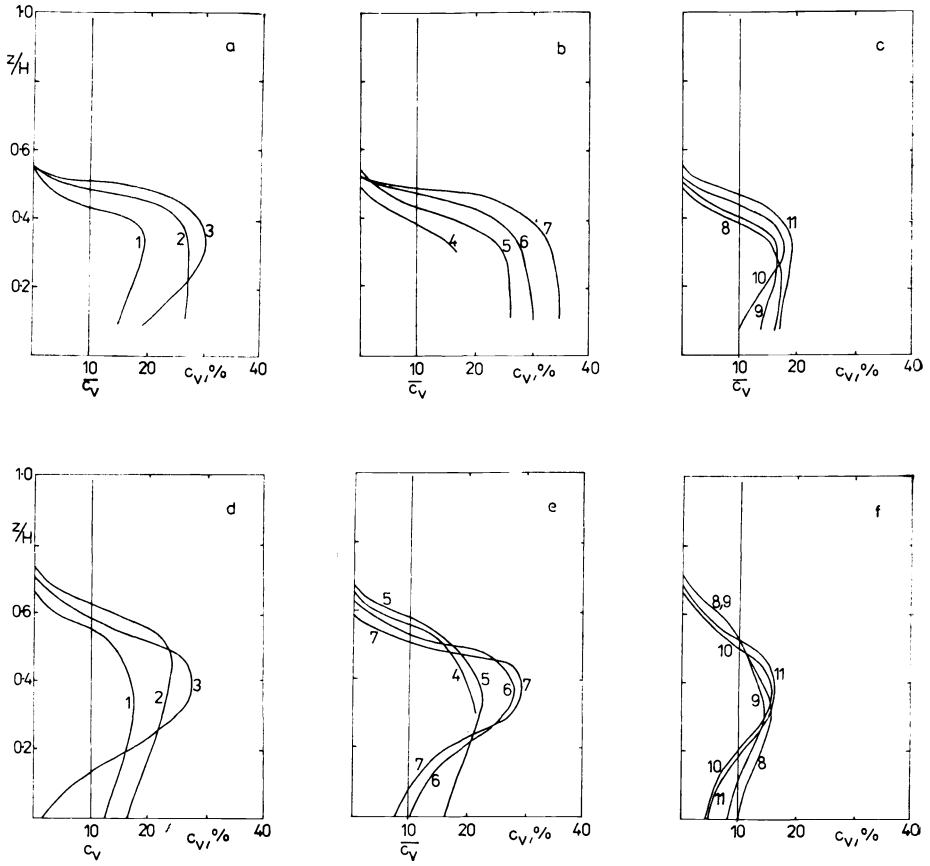

FIG. 8

Axial concentration profiles $d_p = 419$ μm, $\bar{c}_v = 10\%$

in suspension state (Fig. 7d–f). The highest concentration is in about 1/2 of the liquid column height and in contrast to lower impeller velocity the tangential concentration profile plays a more significant role here – we find the concentration growth in the baffle plane again. The radial concentration profile is negligible in the lower part of the vessel, concentration falls slightly towards the wall in its upper part.

By 600 r.p.m. (Fig. 7g–i) a good suspension homogeneity is reached. Concerning the tangential concentration profile, higher concentration in points facing the baffle than in points between the baffles is appreciable. The radial concentration profile is negligible in the baffle plane. Concentration fall towards the vessel wall was observed in the region between two baffles.

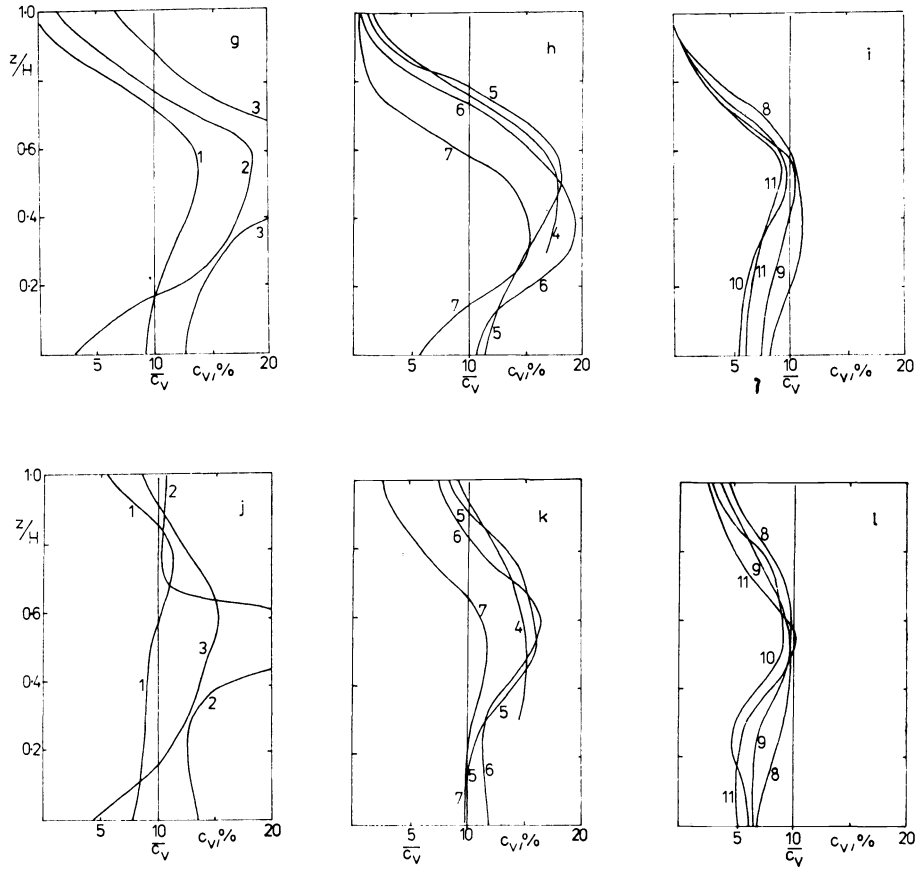

FIG. 8
(*Continued*)

4. $d_p = 419\ \mu m\ ,\quad \bar{c}_v = 10\%$

By 500 r.p.m. (Fig. 8a–c) a layer of particles 20 mm high is shoved to the vessel wall corner. Floating particles reach maximum 1/2 of the liquid column height. Concentration grows towards the wall whereby particles are forced up in the liquid stream. Concentration is higher in points facing the baffle and in the plane 22·5° from the baffle than in the plane between two baffles. Flow in the vessel is calm, without vortices and axial concentration profiles are similar in all 11 points.

By 700r.p.m. (suspension state) concentration grows extremely in about 2/5 of the liquid column height (Fig. 8d–f). The highest concentration is near the vessel wall in this height and falls towards its axis. On the contrary, concentration falls towards the wall near the bottom and in the upper third of the liquid column (particles reach about 2/3 of its height). Concerning the tangential concentration profiles concentration is lower in the plane between two baffles than in the other two planes,

By 900 r.p.m. the solid phase particles reach the liquid surface but the suspension homogeneity is poor (Fig. 8g–i). Concentration falls from the baffle plane towards. the region between two baffles. It is possible to observe a concentration decline towards the vessel wall in this region.

We accomplished the concentration profiles measurement by the aeration state here – 1 100 r.p.m. (Fig. 8j–l). The shape of axial concentration profiles is similar to that by 900 r.p.m. (Fig. 8g–i) but the suspension homogeneity is better. In spite of that, the differences in radial and tangential directions remain great. While the axial concentration profiles are in the main regular and coincident in the plane between two baffles, a severe concentration growth is observed in the baffle plane in about 3/5 of the liquid column height. This fact is connected with the suspension aeration because the greatest vortices are formed on the liquid surface in places near the baffle, where two suspension streams from regions of neighbouring baffles encounter.

DISCUSSION

As evident from the preceding text, radial and tangential concentration differences are considerable, especially by lower r.p.m. Therefore we will try to find the answer to the following question: Is it possible to neglect these differences and carry out the axial concentration profiles measurement in one point in each distance from the vessel bottom only with a satisfactory precision? We have used a method of the variance test[10] for the statistic treatment of previous results. By means of this method we verified the assumption that the variance of a file of data is smaller or equal to an acceptable minimum value. We made the solution on 1% significance level for a maximum variance σ_{hn} which value was counted as a relative part of $c_{vhn} \cdot c_{vhn}$

was an average solid phase concentration in all 11 points situated in the height h above the vessel bottom and corresponding to the r.p.m. value n.

1. $d_p = 1\,343\ \mu m\,, \quad \bar{c}_v = 2{\cdot}5\%$

All σ_{hn} values are less then 10% c_{vhn} above the suspension state and it is possible to get precise results when measuring in one point in each distance from the vessel bottom only. No σ_{hn} value exceeds 20% c_{vhn} by 500 r.p.m. These results are (if we take into account other inaccuracy of measuring method) also acceptable. Only for 300 r.p.m. the results are also significant for $\sigma^*_{hn} = 25\%\ c_{vhn}$ and necessary precision of measurement is not guaranteed by measuring in one point only.

2. $d_p = 1\,343\ \mu m\,, \quad \bar{c}_v = 10\%$

The σ_{hn} values grow above 50% c_{vhn} when the average solid phase concentration is 10%. It is clear that it is impossible to get precise results when measuring in one point in each distance from the vessel bottom only.

3. $d_p = 419\ \mu m\,, \quad \bar{c}_v = 2{\cdot}5\%$

The assumption $\sigma_{hn} < 10\%\ c_{vhn}$ is kept here in all the vessel volume above the suspension rotation and in the lower part of the vesscl even under this state. The variance values σ_{hn} do not exceed 25% c_{vhn} in the upper half of the vessel now and it is possible to consider the results obtained when measuring in one point only to be acceptable.

4. $d_p = 419\ \mu m\,, \quad \bar{c}_v = 10\%$

The suspension homogeneity is a little better than in case of large particles (paragraph 2) but, however, the results are highly significant even for $\sigma^*_{hn} = 25\%\ c_{vhn}$. It is not possible to use the method of concentration measurement in one point only.

We can state that the simpliest method of measuring the concentration in one point in each distance from the vessel bottom is usable when the average solid phase concentration is 2·5%. Accuracy of the results is higher when solid particles dimensions are small. This method does not reach the demanded accuracy when the average concentration grows up to 10% and must be cut off. However, we will go on trying to find a solution which is precise enough and less time-spending than measurement in all 11 points. We can see when studying the axial concentration profiles in Figs 5–8 that the tangential concentration profiles are more essential (at least above the suspension state) than the radial ones. Therefore we suggested hypothesis that it is sufficient to measure concentration profiles tangentially – it means in one point in each of the baffle plane and of planes 22·5° and 45° from it and neglect radial

concentration differences in these planes. We verified this assumption by means of the same statistic method used in the preceding paragraph.

We can reach a satisfactory accuracy with the suspension and higher r.p.m. for $d_p = 1{\cdot}343$ μm and $c_v = 10\%$ when using the 3-points measuring method but some results are significant even for $\sigma^*_{hn} = 25\%\ c_{vhn}$ on the 1-% significance level (points in upper part of the vessel situated in the baffle plane and in the plane 22·5° from the baffle). It occurs due to the great concentration growth in point 3 (collision of streams coming from regions between the neighbour baffles) and its drop in point 5 (near to the impeller shaft). It is possible to accept this hypothesis with these exceptions.

Results are better for $d_p = 419$ μm. It is possible to accept the hypothesis with the same exceptions as in case of large particles (the concentration growth is apparent not in point 3 but in point 2).

CONCLUSION

The goal of our research was to estimate the solid phase concentration distribution in a mixed vessel. Results of our measurement are shown in form of axial concentration profiles in Figs 5–8. Except of visible axial local concentration differences it is possible to observe also the radial ones which cannot be neglected especially by lower r.p.m. (solid phase concentration grows from the vessel axis towards its wall) and tangential ones (higher solid phase concentration in the baffle plane than in the region between two baffles) essential, on the other side, by higher r.p.m. Radial differences are negligible in comparison with the tangential ones in the suspension state.

After the statistic treatment of results we made a conclusion that it is not necessary to carry out the concentration profiles measurements in a great number of points in industrial conditions where very precise local concentration values are not required. It is sufficient to measure one axial concentration profile in one point in each distance from the vessel bottom when the average solid phase concentration does not exceed 3%. We recommend point 6 for large particles and point 5 for small ones according to Fig. 4. Tangential concentration differences cannot be neglected when the average solid phase concentration is greater. However, it is not necessary to take into account the radial differences. Thus it can be measured in one point in each of the planes of the baffle and 22·5° and 45° from the baffle. We recommend points 2, 6, 9 for large particles and 3, 6, 9 for smaller ones ($d_p < 1$ mm) according to Fig. 4.

It is not possible to get precise results when using this method for r.p.m. smaller than the suspension speed is. If it is necessary to measure concentration profiles under the suspension state it must be measured in a greater number points as for example in points 1–11 given in Fig. 4. The same is of course also necessary in cases when our interest is to get a perfect concentration distribution.

SYMBOLS

b	width of the baffle, m
c	solid phase concentration (generally)
c_v	relative local volume concentration
$\bar{c}_v$	average relative volume concentration
c_{vhn}	relative volume concentration corresponding to the conductivity probe distance from the vessel bottom h and impeller speed n
d	impeller diameter, m
D	mixed vessel diameter, m
d_p	average solid phase particles diameter, m
G_p	relative electric conductivity
h	distance of conductivity probe from the vessel bottom, m
H	liquid column height in the vessel, m
H_2	impeller distance from the vessel bottom, m
n	impeller speed, s^{-1}
R	initial resistance on the resistance decade, Ω
ΔR	resistance change step on the resistance decade, Ω
γ_b	relative electric conductivity of suspension, S m^{-1}
γ_p	relative electric conductivity of liquid, S m^{-1}
γ_f	relative electric conductivity of solid phase, S m^{-1}
δ	displacement of the recorder
σ	variance
σ^*	maximum acceptable variance
σ_{hn}	variance corresponding to the conductivity probe distance from the vessel bottom h and impeller rotation n

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