LIQUID CIRCULATION IN A CYLINDRICAL BAFFLED VESSEL OF HIGH HEIGHT/DIAMETER RATIO WITH TWO IMPELLERS ON THE SAME SHAFT*

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Received January 21st, 1987

The paper deals with the experimental study of the indicating particle circulation in a liquid mechanically agitated with two high-speed impellers (two standard turbine impellers or a lower standard turbine and upper six inclined (at 45°) plane blade impeller) on the same shaft in a slender vessel (its height equals double of the vessel diameter) equipped with four radial baffles at its walls under the turbulent flow regime of agitated charge. The visual method of observation of the indicating particle is used to investigate the model system. Four types of the particle circulation are examined: its circulation in the lower part of the system (pumping effect of the lower impeller), its circulation in the upper part of the system (pumping effect of the upper impeller), and the exchangeable circulation between the upper and lower part of the system and *vice versa*. It follows from the obtained average data of the above-mentioned circulations that the homogeneous circulation of charge in the whole system is reached providing the vertical distance of the high-speed impellers is equal to at least double of their diameter, their pumping capacities being approximately double compared to those reached in the system with one impeller where the off-bottom liquid level height is equal to the vessel diameter. It follows from the comparison of two arrangements, when the upper high-speed impeller pumps liquid either upwards or downwards, that the homogeneous circulation of all the charge agitated is attained in the first of both the cases compared.

Intensification of technological processes in the chemical and food industry brings about new demands on the increase in utilization of raw materials processed with simultaneous cutting down on the built up area in plants. This reflects in increasing the height of agitated systems on retaining their diameters. This practice is introduced especially where air is blown into such systems which serves here for technological processes, *e.g.*, in fermenters or leaching devices. Circulation of the bulk phase (liquid) in such systems contributes considerably to the spatial homogeneity of the process (*e.g.*, to the microorganism grow, flotation of solid phase suspensions, *etc.*).

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* Part LXXI in the series Studies on Mixing; Part LXX: Collect. Czech. Chem. Commun. *52*, 1888 (1987).

The knowledge of conditions on which the carrier medium cirulation in slender vessels is uniform can consequently lead to the optimization of shape and arrangement of the equipment for the technological process considered.

Considerable attention has been paid in the literature[1-6] to the liquid circulation in agitated systems with "the standard arrangement" (the diameter of cylindrical vessel equipped with radial baffles at its wall is equal to the height of the agitated liquid level above the bottom) with high-speed impellers under the turbulent regime of the charge flow. The circulation has been examined by visual observation of the indicating particle, and the time has been measured needed to pass the characteristic loop, *e.g.*, from the region surrounding the rotating impeller (a so-called rotor region of impeller) back to this region (a so-called primary circulation loop) characterizing the pumping capacity of impeller. This effect could be calculated quantitatively from the knowledge of the average time of the above-mentioned circulation or expressed in dimensionless form as the flow rate number. Under the turbulent regime of agitated charge, its value does not depend on Reynolds number Re_M, however, depends on the geometry of agitated system (type of impeller, its location in the system, and the like). Circulation in "the standard arrangement" of agitated system with two high-speed impellers on the same shaft (dual impellers) under the laminar and/or transition regime of flow of agitated charge ($Re_M < 160$) was investigated by Nienow and Kuboi[7]; thier measurements were automated by means of a TV--camera and video recorder. They interpreted the results of their measurements in terms of circulation models characterized by a certain number of circulation vortexes whose number depended on the types of certain impellers (axial or radial impeller) and on the fact whether the upper (axial) impeller pumped liquid upwards or downwards. The circulation of liquid agitated with dual standard turbine impellers in a cylindrical system whose height equals double of the vessel diameter was investigated, on using the electric (magnetic induction) indication of the passage of indicating particle through a selected plane of the system, by Mukataka and co-workers[6]. The circulation time for the given impeller was defined as the time which indicating particle needed to repass through the rotor region of the same impeller, without passing the rotor region of the second impeller. The transfer of the magnetic indicating particle from one rotor region to that of the second impeller gives then the information on the convective mass exchange between both the circulation regions. The experiments were made with a suspension of paper in water simulating the rheological behaviour of a microbial suspension in fermenter; the regime of the agitated charge flow ranged from laminar to transition.

The more impellers the agitated system contains, the more complicated is the description of the circulation model[8]. For a system with one impeller it is sufficient to know the average time of primary circulation and the volume of agitated charge. However, for more impellers in the system, we need to know more quantities, partly because each impeller and its surroundings form one subsystem, partly because the mass transfer (circulation) takes place between each two adjacent subsystems.

THEORETICAL

The aim of this study is to propose an efficient arrangement with dual impellers to reach the homogeneous liquid circulation in the whole volume of agitated charge whose height is H above the cylindrical vessel bottom (see Fig. 1) equipped at its walls with radial baffles of width l, is equal to double of its diameter D. Two types of impellers were used for mixing. The lower, always standard (Rushton type) turbine impeller[9] (Fig. 2), is located at $H_2 = D/3$ off-bottom. As the upper one, either a standard turbine impeller is used as well (arrangement A) or a six inclined plane blade impeller[3,9] (see Fig. 2 as well) which pumps liquid either downwards (arrangement B), or upwards (arrangement C). The distance between the upper and lower impellers Δc is varying. The liquid circulation takes place under its turbulent flow regime.

To watch the passages of the indicating particle between the rotor regions, the liquid volume is divided into two parts (see Fig. 1): Region I corresponds to the volume around the lower impeller to the height $H_2 + 0{\cdot}5\ \Delta c$ and region II corresponds to the remaining volume of charge around the upper impeller. For the two regions,

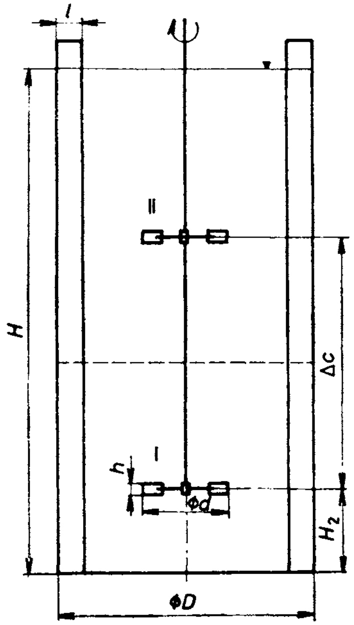


Fig. 1

Agitated system with dual high-speed impellers four transitions (circulations) of the indicating particle are defined: transition I – circulation between two successive passages of the indicating particle through the rotor region of the lower impeller without passing through the rotor region of the upper impeller; transition II – circulation between two successive passages of the indicating particle through the rotor region of the upper impeller without passing through the rotor region of the lower impeller; transition I–II and II–I – circulation of the indicating particle between the rotor regions of the lower and upper impeller (I–II) or the other way round (II–I). The measured circulation time of indicating particle is considered in the following way:

1) Total time of circulation θ_t – time taken in measuring the circulation.

2) Total time of motion of the indicating particle in the single region $\theta_{t,i}$ (i = I, II, I–II, II–I).

3) Average time of circulation of the indicating particle in the single region

$$\theta_{av,i} = \theta_{t,i}/m_i\,, \quad (i = \mathrm{I, II, I{-}II, II{-}I})\,. \qquad (1)$$

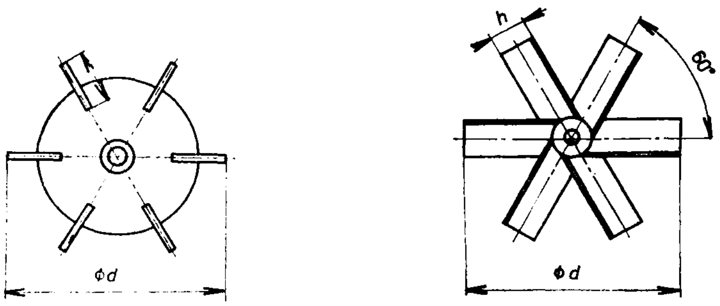
The following relations hold between the circulation quantities $\theta_{t,i}$ and $\theta_{av,i}$:

$$\theta_t = \sum_i m_i \theta_{av,i}\,, \quad (i = \mathrm{I, II, I{-}II, II{-}I})\,, \qquad (2)$$

and/or on using Eq. (*1*)

$$\theta_t = \sum_i \theta_{t,i}\,, \quad (i = \mathrm{I, II, I{-}II, II{-}I})\,, \qquad (2a)$$

where m_i is the number of single transitions.



a *b*

FIG. 2

Rotary high-speed impellers used: *a* standard (Rushton) turbine six blade disc impeller ($h = 0{\cdot}2d$), *b* inclined (at 45°) plane blade impeller ($h = 0{\cdot}2d$)

The circulation time of liquid particle is determined by the length of circulation loop and by velocity at each its point. Since the liquid velocity differs at each point of agitated charge and each circulation loop is of different length, the time of circulation has a certain distribution characterizing the circulation flow. For each system region, its volume V_i (i = I, II, I–II, II–I) is defined. The relations for these volumes are given in Table I. For the turbulent flow of agitated charge, when the Reynolds number for mixing

$$\mathrm{Re_M} > 5\cdot0 \,.\, 10^3 \,, \tag{3}$$

it is possible to assume that the region volumes considered are fully filled-up with circulating charge – the existence of dead (non-agitated) regions in the system is not considered. Then the volumetric flow rate through the i-th region can be determined from the relation

$$\dot{V}_i = V_i/\theta_{\mathrm{av},i}\,, \quad (i = \mathrm{I, II, I–II, II–I})\,. \tag{4}$$

The above-mentioned characteristics of circulation in the system investigated can be expressed in the dimensionless form: dimensionless average time of circulation $\theta_{\mathrm{av},i} \,.\, n$, ($i$ = I, II, I–II, II–I),
flow rate number

$$\mathrm{Kp}_i \equiv \dot{V}_i/nd^3\,, \quad (i = \mathrm{I, II, I–II, II–I})\,, \tag{5}$$

and the relative time of the particle stay in region i

$$\theta_{\mathrm{t},i,\mathrm{rel}} = \theta_{\mathrm{t},i}/\theta_{\mathrm{t}}\,, \quad (i = \mathrm{I, II, I–II, II–I})\,. \tag{6}$$

All the quantities said depend on the impellers distance Δc which can be expressed in dimensionless form as $\Delta c/d$.

TABLE I

Relations for calculating volumes V_i of regions in agitated system for arrangements A, B, and C

i	A	B	C
I	$0\cdot25\,\pi D^2(H_2 + \Delta c/2)$	$0\cdot25\,\pi D^2(H_2 + \Delta c/2)$	$0\cdot25\,\pi D^2(H_2 + \Delta c/2)$
I–II	$0\cdot25\,\pi D^2\,\Delta c$	$0\cdot25\,\pi D^2(H - H_2 - \Delta c/2)$	$0\cdot25\,\pi D^2\,\Delta c$
II–I	$0\cdot25\,\pi D^2\,\Delta c$	$0\cdot25\,\pi D^2\,\Delta c$	$0\cdot25\,\pi D^2(H - H_2 - \Delta c/2)$
II	$0\cdot25\,\pi D^2(H - H_2 - \Delta c/2)$	$0\cdot25\,\pi D^2(H - H_2 - \Delta c/2)$	$0\cdot25\,\pi D^2(H - H_2 - \Delta c/2)$

EXPERIMENTAL

The principle of the method consisted in visual observation of motion of the indicating particle[2] (see Fig. 3) in charge and storage of its passages through the rotor regions of single impellers by means of a joystick into the store of an IQ-151 computer. The joystick (see Fig. 4) has an operating handle movable only along one axis. It enables to set so three positions: neutral, up, and down. In case that the indicating particle moves outside the rotor regions of impellers, the handle is in position "neutral". If it passes through the rotor region of the lower impeller, the handle is deflected downwards, and if it passes through the rotor region of the upper impeller, the handle is deflected upwards. In the phase of sensing the time course of the indicating particle circulations, the computer, on the basis of a given program, continuously registers the position of the joystick handle. As soon as the handle is deflected from neutral, the program begins to storage the time at which the deflection occurs and the handle position, as well. In the phase of processing, the found values of current time are converted to time intervals between single changes of the joystick position. These intervals are further classified according to the handle position at the beginning and at the end of the interval to four groups: "down–down", "from down–upwards", "up–up", and "from up–downwards" which correspond to the above-defined transitions (circulations) I, I–II, II, and II–I. In this way we obtain, within the framework of one experiment, for single transitions, the values $\theta_{av,i}$ and m_i, and moreover, the maximum and minimum time of the respective circulation (transition) $\theta_{max,i}$ and/or $\theta_{min,i}$, as well as the standard deviation of the single set of circulations, σ_i.

The measurements were carried out in a cylindrical vessel (see Fig. 1) of inside diameter $D = 0{\cdot}29$ m and filling height $H = 0{\cdot}58$ m, located in a square vessel of inside edge length $a = 0{\cdot}396$ m, filled with tempering water and water-glycol solution. Both vessels were made of perspex. Along the whole height of the cylindrical vessel, four radial baffles of width $l = 0{\cdot}1D$ were located symmetrically. In the vertical axis of symmetry of the vessel, dual impellers (see

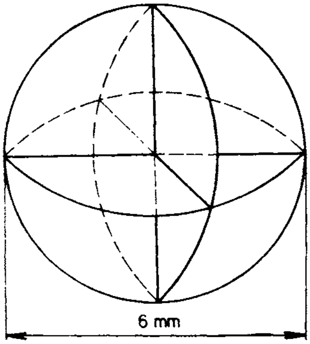


FIG. 3

Indicating particle

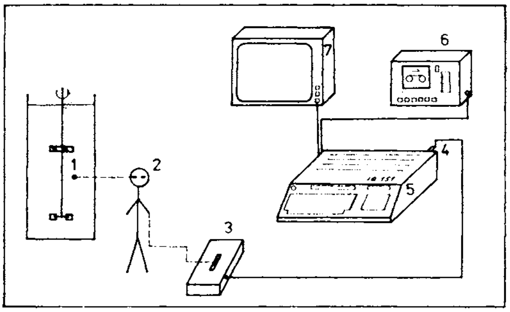


FIG. 4

Block scheme of the apparatus for measuring the circulation of indicating particle in the system with dual impellers. 1 indicating particle in charge, 2 experimenter, 3 joystick, 4 interface, 5 IQ-151 computer, 6 monitor, 7 monitor tube

Fig. 2) were located in the arrangement A, B, or C (see above). Diameter of all the impellers used was $d = 0{\cdot}097$ m; the ratio $d/D = 1/3$. The vessel was filled-up with 6 per cent aqueous NaCl solution of density $\varrho = 1\,044\ \mathrm{kg/m^3}$ equal to the density of material of the indicating particle used. The temperature at which the measurement was taken was within the range of 20—22°C, the impeller frequency of revolution n was set within $2{\cdot}5$—$7{\cdot}5\ \mathrm{s^{-1}}$ and it was measured by means of a photoelectric sensor. The measurements were performed within the impeller distance $\Delta c \in \langle 1{\cdot}2d;\ 3d\rangle$. For the given value of Δc, the measurements were taken at three levels of the impeller frequency of revolution. Setting the lowest value was conditioned by the turbulent regime of charge. The highest set value of frequency of revolution was limited by the ability of experimenter to distinguish two successive passages of indicating particle through the rotor region of the given impeller.

The dimensions of impellers and vessel, as well as the distance between the impellers and liquid level and bottom were measured with a milimeter scale with the accuracy of $\pm 5 \,.\, 10^{-4}$ m. The impeller frequency of revolution was measured with a photoelectric sensor: The relative measuring accuracy of this quantity reached at most $\pm 1{\cdot}6\%$ of the set value of frequency. The density of charge in investigations performed was within $1\,043$—$1\,044\ \mathrm{kg/m^3}$, its viscosity within the range $1{\cdot}03 \,.\, 10^{-3}$—$1{\cdot}07 \,.\, 10^{-3}$ Pa s. The dependent variable quantity, time of circulation, was measured by means of the joystick whose sensitivity was $\pm 0{\cdot}1$ s. The accuracy of the measurement by experimenter amounted to $\pm(0{\cdot}2$—$0{\cdot}3)$ s.

One experiment was always performed for an impeller distance Δc and its frequency of revolution. It corresponded to the overall number $\sum m_i \approx 3\,000$ transitions (circulations) of indicating particle; for one set of conditions (arrangement A, $\Delta c = 2{\cdot}5d$, $n = 320\ \mathrm{min^{-1}}$), the evaluation of experiments was carried out gradually for $\sum m_i = 1\,000,\ 2\,000,\ 3\,000,\ 4\,000$, and $5\,000$ transitions (circulations). The test of accuracy of the determination of the single average circulation time $\theta_{\mathrm{av},i}$, ($i =$ I, II, I–II, II–I) (ref.[10]) was made from these data. It followed from the tests of the difference significance of two expected values that the total number of transitions $\sum m_i = 2\,000$ was sufficient for our experimental arrangement.

During the whole series of measurements, the value of the mixing Reynolds number was within $\mathrm{Re_M} \in \langle 5{\cdot}234 \,.\, 10^4;\ 7{\cdot}02 \,.\, 10^4\rangle$ so that the flow regime of agitated charge was therefore turbulent.

RESULTS AND DISCUSSION

For each relative position of impellers (variable Δc or $\Delta c/d$) in all three arrangements A, B, and C examined, the values of dimensionless variables Kp_i (Eq. (5)), $\theta_{\mathrm{av},i} \,.\, n$, $\theta_{\mathrm{t},i,\mathrm{rel}}$ (Eq. (6)) for each measured level of the impeller frequency of revolution n were calculated from measured data. Although this quantity varied by 250% the above-mentioned dimensionless quantities did not fluctuate within the interval greater than ±10% about the average values of $\langle \mathrm{Kp}_i\rangle$, $\langle \theta_{\mathrm{av},i} \,.\, n\rangle$, and $\langle \theta_{\mathrm{t},i,\mathrm{rel}}\rangle$ calculated as arithmetic means of these quantities found for three levels of quantity n. This procedure is in agreement with the results of cited works[2-4] where it is stated that under the turbulent regime of the flow of agitated charge ($\mathrm{Re_M} > 5{\cdot}0 \,.\, 10^3$), the flow or circulation characteristics of agitated charge do not depend on the value of Reynolds number. However, they do depend on the number of circulations observed from which the sought hydrodynamic characteristics are calculated[2]. Therefore, the number of circulations $\sum m_i = 100$, from which the mentioned characteristics were calculated by authors[7], seems not to be sufficient even for the laminar flow regime of agitated charge maintained in the work cited.

Flow rate number Kp_i, $(i = \mathrm{I, II})$ for the dual turbine impellers (*arrangement* A) with distance $\Delta c = (2-3)\,d$ (see Fig. 5), approximately equals double of the flow rate number for the single impeller in the system where the condition[4,5] $H = D$ holds. Between the distances $\Delta c \in \langle 1{\cdot}8d;\, 2{\cdot}0d \rangle$, a step change in the flow rate number value occurs, this value being again constant for lower distances between the impellers, however, $Kp_\mathrm{I} < Kp_\mathrm{II}$. It is possible to judge from the assumed circulation models (see Fig. 6) in this arrangement that with a sufficient distance of the impellers, their flow patterns do not influence and are the same for each impeller as in case

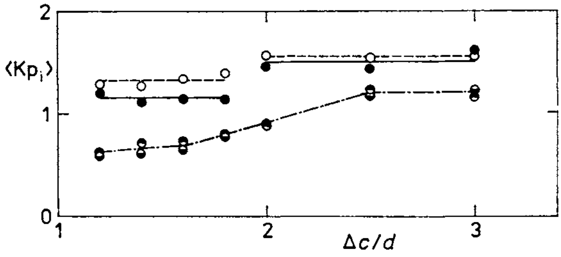


FIG. 5

Dependence of the flow rate number on the relative impeller distance for arrangement A. *i*: I (●; ———), I–II (◒; — · —), II–I (◓; — · —), II (○; — — —)

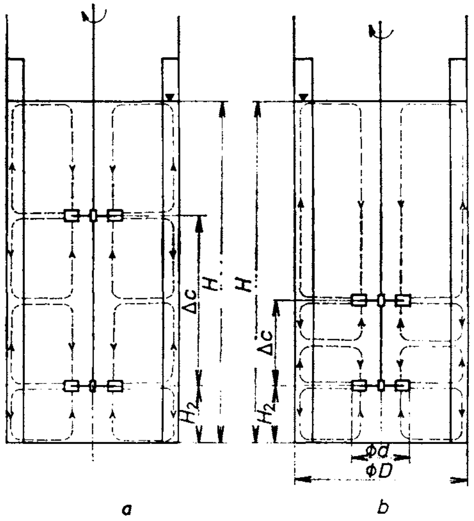


FIG. 6

Flow patterns for arrangement A: *a* $\Delta c/d = 3$, *b* $\Delta c/d = 1{\cdot}5$

of flow patterns with one impeller. Higher pumping capacities are reached to the detriment of decreasing the friction losses in the horizontal plane separating the circulation regions of both impellers in comparison with the phase boundary (bottom or liquid level). In case of smaller distance between the impellers, the streams streaking from the single impellers influence each other and in case of the lower impeller, even its interruption occurs. Consequently, the values of quantities Kp_i, (i = I, II) decrease in comparison with the previous state. This fact follows, after all, from measuring the power input characteristics in the arrangement[8] discussed from which follows that if the relation $\Delta c \geqq 2d$ holds, the power input of the dual turbine impellers can be determined as double of power input of single impeller. At smaller distances between the impellers, the value of their common power input significantly decreases.

The relative time of the indicating particle stay is for *arrangement* A in region II greater than in region I (see Fig. 7). It is so because the space above the upper impeller increases with decreasing distance Δc. The indicating particle consequently needs much more time to pass through the upper loop of the upper impeller (see Fig. 6*b*) than in case of a uniform location of impellers along the shaft. It can be therefore recommended for the arrangement of the agitated system ($H = 2D$) used by us, the distance between the impellers to be equal at least to double of their diameter.

Flow rate number Kp_I for the turbine impeller in *arrangement* B is equal to about 1·5-fold the flow rate number for single impeller in case of the system where[4,5] $H = D$. From the course of values Kp_I and Kp_{II} at various magnitudes of simplexes $\Delta c/d$ (see Fig. 8) follows that the characteristics given approach each other when decreasing the quantity $\Delta c/d$. The values Kp_I and Kp_{II} are practically equal for distance $\Delta c = 1{\cdot}6d$, the flow patterns of both impellers influencing each other significantly. Providing that the impellers are distant from each other at least by

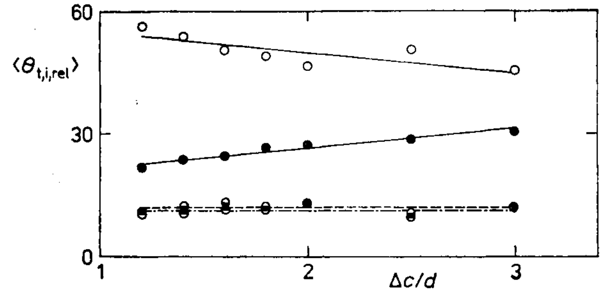


FIG. 7

Dependence of the relative time of stay of the indicating particle in the given region of system on the relative impeller distance for arrangement A. For designation see Fig. 5

double of their diameter, the relative time of the indicating particle stay in region I does not nearly differ from that in region II (see Fig. 9). This can be explained by the fact that the action of flows of different (opposite) directions at the boundary of regions I and II, the equalization of relative times of stay of the indicating particle in single region takes place. The opposite direction of flow of adjoining streams at the boundary of regions I and II (see Fig. 10), is, however, the reason of additional energy losses by friction between the mentioned streams, which decreases the circulation (pumping) effects of both impellers.

Flow rate number Kp_I for the turbine impellers in *arrangement* C is approximately equal to double of the flow rate number for single impeller[4,5] and quantity Kp_{II} for the six blade impeller in the given arrangement (see Fig. 11) is approximately equal to 1·2-fold the flow rate number for single impeller[3] in case of the system where $H = D$. When approaching the impellers, the flow patterns do not influence (neither quantity Kp_I nor quantity Kp_{II} changes with decreasing the value of simplex $\Delta c/d$)

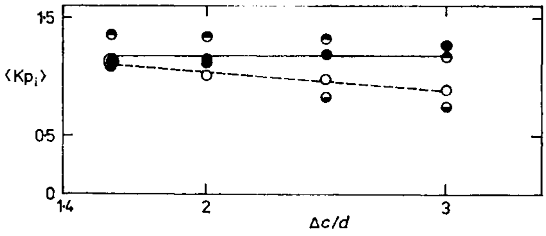


FIG. 8

Dependence of the flow rate number on the relative impeller distance for arrangement B. *i*: I (●; —), I–II (◒), II–I (◓), II (○; – –)

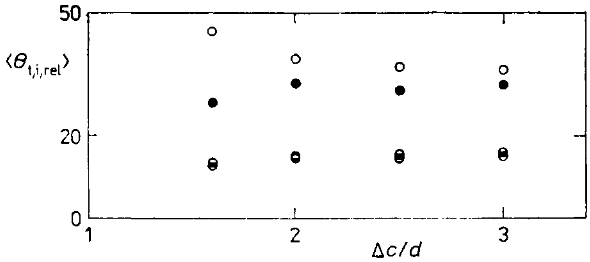


FIG. 9

Dependence of the relative time of stay of the indicating particle in the given region of system on the relative impeller distance for arrangement B. *i*: I (●), I–II (◒), II–I (◓), II (○)

probably because the directions of flows, where the circulation loops touch, are identical.

The relative time of stay of the indicating particle in region I decreases with decreasing value of Δc, in region II, on the contrary, increases with decreasing value of Δc (the off-bottom distance H_2 of the lower impeller not being changed) (see Fig. 12), the sum of these relative times not being dependent on the impeller distance. This effect is to be accounted for considering that the upper axial impeller with pumping effect upwards entrains the liquid from region I to region II. This entrain-

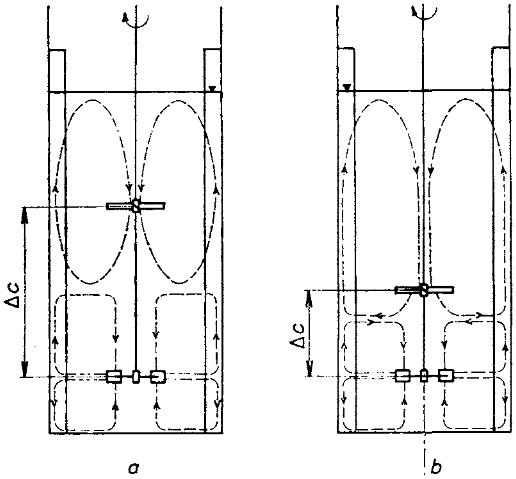


Fig. 10

Flow patterns for arrangement B: *a* $\Delta c/d = 3$, *b* $\Delta c/d = 1{\cdot}5$

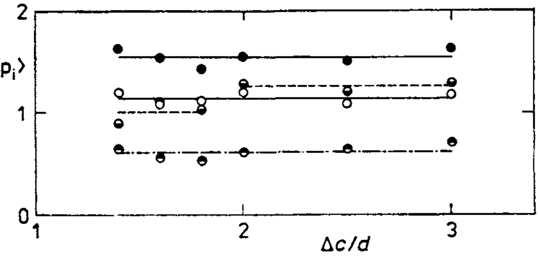


Fig. 11

Dependence of the flow rate number on the relative impeller distance for arrangement C. For designation see Fig. 5

ment is due to the coincident direction of flow at the boundary of both these regions, which, after all, contributes to the decrease of friction losses between the circulating flows at the given bounary surface (see Fig. 13). As to the properties of flow pattern, system C is then closer to system A than to system B.

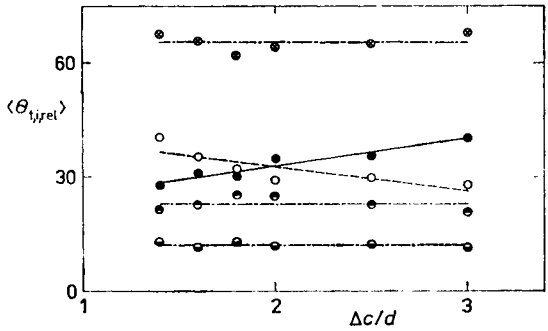


Fig. 12

Dependence of the relative time of stay of the indicating particle in the given region of system on the relative impeller distance for arrangement C *i*: I (●; —), I–II (⊖; — · —), II–I (⊖; — · —), II (○; — —), I + II (⊗; — · —)

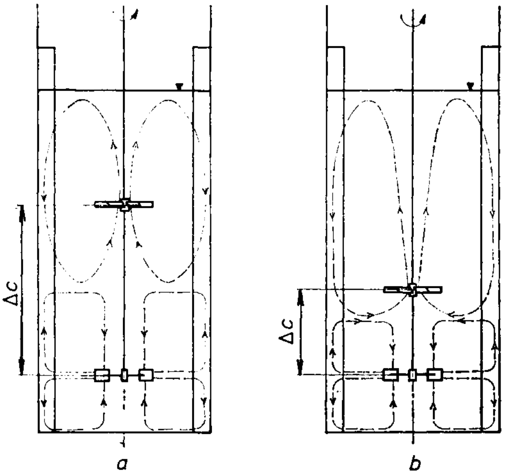


Fig. 13

Flow patterns for arrangement C: *a* $\Delta c/d = 3$, *b* $\Delta c/d = 1{\cdot}5$

CONCLUSIONS

As suitable arrangements for vessels of high height/diameter ratio, it is possible to use a dual combination of turbine impellers whose distance is greater than double of the impeller diameter or a dual combination of a turbine and an inclined plane blade impeller, with pumping effect upwards, whose distance is greater than 1·4-multiple of the impeller diameter. In both these arrangements, both the impellers do not influence each other and serve well both for the homogeneous dispersion of gas blown into the charge (lower turbine impeller) and for the intensive circulation (upper turbine or blade impeller) and so also for the homogenization of the liquid phase in the whole volume of agitated system.

LIST OF SYMBOLS

a	length of inside edge of square vessel, m
Δc	(mutual) vertical distance of impellers, m
D	inside diameter of cylindrical vessel, m
d	impeller diameter, m
H	filling height of vessel, m
H_2	off-bottom distance of lower impeller, m
h	height of impeller blade, m
Kp	flow rate number
l	width of radial baffle, m
m	number of passages of indicating particle through chosen volume
n	impeller frequency of revolution, s^{-1}
$\mathrm{Re}_M = nd^2\varrho/\eta$	mixing Reynolds number
V	volume, m^3
$\dot{V}$	volumetric flow rate, $m^3\ s^{-1}$
η	dynamic viscosity, Pa s
θ	time of circulation, s
σ	standard deviation of distribution of circulation times, s
ϱ	density, kg m^{-3}

Subscripts and Designations

av	average value in set
i	referred to i-th region of systems
min	minimum value
max	maximum value
t	referred to whole
I	referred to lower impeller
II	referred to upper impeller
I–II	referred to transition between lower and upper impeller
II–I	referred to transition between upper and lower impeller
$\langle\ \rangle$	arithmetic mean of values over varying impeller frequency of revolution

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Translated by J. Linek.