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NUMERICAL INVESTIGATIONS OF DISCHARGE FLOW AND CIRCULATION FLOW IN AN UNBAFFLED MIXING VESSEL AGITATED BY A PLAIN DISK

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ABSTRACT

Numerical simulations of flow in an unbaffled mixing tank agitated by a plain disk were performed using the CFD software package Fluent. Pre-processing was done using another software package called Gambit, while post-processing was done using an in-house software based on Matlab code. The circulation and discharge flow rates and their respective non-dimensional numbers were investigated. The locus of the recirculation centre has been found to follow a deformed "*C*" like path, for a centrally located disk. The circulation flow rate was observed to be linearly dependent on the *Re* and also on the disk size. The range of clearance values, $0.25 \leq C \leq 0.50$, has been seen to produce the same discharge and circulation flow rates for a given disk size. A smaller clearance $C = 0.15T$ resulted in reduction of *Qc* & *Nqc* and & *Nqp*. The discharge flow rate was seen to be dependent on both the *Re* and the disk size. The values of *Nqc* and *Nqp* found here are smaller than the ones for radial flow impellers. Both the circulation and discharge flow numbers appear not to be constant over the "entire" range of *Re*.

NOMENCLATURE

C	Agitator off-bottom clearance (m)
D	Agitator diameter (m)
H	Liquid height in the vessel (m)
N	Agitator rotational speed (rps)
Nqc	Circulation flow number (-)
Nqp	Discharge (pumping) flow number (-)
Np	Power number (-)
Qc	Circulation flow rate (m^3/s)
Qc1	*Qc* between the recirculation centre (*Rc*) and the shaft; *Qc2* and between *Rc* and the tank cylindrical wall
Qp	Discharge flow rate (m^3/s)
rc	Radial position of the recirculation centre (m)
rs	Shaft radius (m)
Re	Reynolds number ($= \rho ND^2)/\mu$ (-)
T	Tank diameter (m)
Vr &*Vz*	Radial and axial velocity components (m/s)
W	Agitator width in the axial direction (m)
Z	Axial direction
ρ	Liquid density (kg/m^3)
μ	Liquid viscosity (Ns/m^2)

<u>*Definitions*</u>:

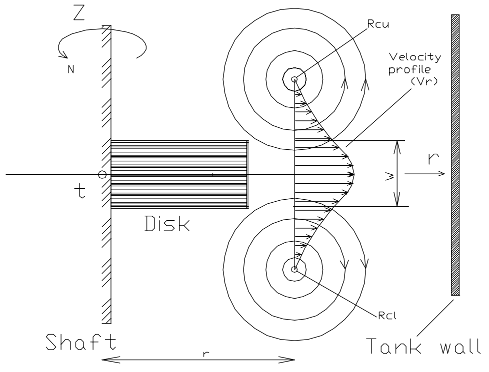


Figure 1 : Radial velocity profile and circulation flow

$$Nqp = Qp/ND^3 \tag{1}$$

$$\text{where } Qp = 2\pi r \int_{-w/2}^{w/2} Vr dz \tag{2}$$

$$Nqc = Qc/ND^3 \tag{3}$$

$$Qc = Qc1 + Qc2 \tag{4}$$

where $$Qc1 = 2\pi \int_{rs}^{rc} (rVz)dz \qquad (5)$$

and $$Qc2 = 2\pi \int_{rc}^{T/2} (rVz)dz \qquad (6)$$

INTRODUCTION

Stirred vessels are widely used in the chemical process industry where mixing operations play an important role throughout the production process. The range of applications is so varied and includes: blending of two liquids, solid suspension accompanied by another process such as leaching and floatation, gas dispersion into a liquid followed by absorption and/or a chemical reaction between liquid and gas, fermentation or crystallisation.

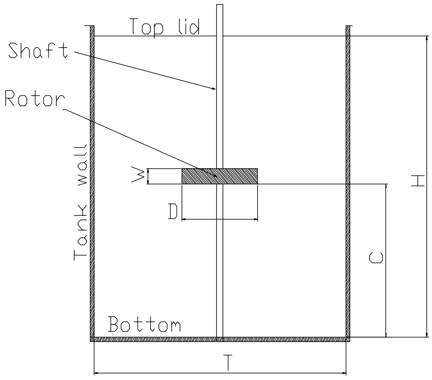


Figure 2. Mixing vessel configuration

In the process industry, there is an increasing need for properly designed mixing vessels to reduce production losses and maintenance costs. The efficiency of many industrial processes greatly depends on the optimization of the mixing parameters. It is therefore important to investigate flow generated in mixing tanks to enable the design of systems with improved efficiencies. As an alternative to experimental investigation, Computational Fluid Dynamics (CFD) constitutes not only a useful tool but also a cost effective means in the design of mixing systems. Using CFD, Bakker *et al.* [1] were able to study the effects of flow pattern on the solids distribution in a stirred tank and found that the solids distribution was strongly affected by certain flow transitions.

One of the most important parts of a mixing vessel system (Fig. 1) is the agitator, also known as the turbine or impeller. Impellers are classified, on the basis of flow pattern, into two major groups namely axial and radial flow. A variety of impeller designs exist but no single one of them is sufficiently versatile perform all the functions of mechanical agitation. In practice impellers are designed to generate a flow pattern that enhances performance for a specific function.

The most widely used mixing vessels are the baffled type and this is evident in the larger share of publications about them found in the literature [2, 3]. However, there are many cases where the absence of baffles presents a number of advantages: for example in applications involving low agitator rotational speed (laminar flow) and high friction on the tank cylindrical wall [4], in crystallisers where the presence of baffles may cause may cause particle attrition phenomenon [5]. Moreover, power consumption in closed and filled unbaffled mixing tanks is approximately half of the value obtained from baffled tanks [6].

Generally flow patterns induced by an agitator are the first indication of its suitability for a particular process. The distribution of solid particles and the dispersion of gas in a liquid largely depend on the type of flow patterns that a particular agitator can produce in a given vessel. The end product of a mixing process depends not only on the physiochemical aspects of the particular process but also on the flow patterns of the different species.

Some of the important factors that dictate the quality of mixing are primary and secondary circulation flow rates and impeller volumetric flow discharge rate. Rushton *et al.* [7] were perhaps among the first investigators to publish data on the actual discharge flow of impellers in mixing vessels. Later, Sachs and Rushton [8] published data on discharge flow for turbine type impellers in baffled tanks

Myers *et al.* [9] showed that there was a transitional clearance value that depended not only on the off-bottom clearance but also on the size and type of agitator. Their results for a radial flow turbine (*S*-4) are in reasonable agreement with the value of C=0.22T suggested by Conti *et al.* [10] for D<0.37, however this value decreased the range D/T>0.37

Costes and Courdec [11] found that the pumping coefficient for a Rushton turbine (D/T=0.33 and C=T/2) was constant in all cases with mean value independent of the stirrer rotational speed or the size of the unit, and equal to 0.73. They also found that the circulation flow rate near the wall of the tank, *Qc2*, was always slightly lower by between 10 and 20%, than the one calculated in the centre of the tank, *Qc1* (Fig. 2). They attributed this difference to experimental errors and they concluded that the circulation flow rate appeared to be proportional to the rotational speed of the turbine. However, the circulation number, *Nqc*, was observed to be independent of the rotational speed and size of the impeller, with an average value of 3.4 ± 0.4, which was found to be about four times bigger than the discharge number, *Nqp*.

A similar study conducted by Nagata [4] found that the ratio between circulation number and pumping number was within the range 1.8 and 1.9, which is almost half of the value obtained by Costes and Couderc [11]. Costes and Couderc's ratio could be more reliable than Nagata's because the latter used pitot tubes as opposed to LDA used by the former. Recently, Lamberto et al [12] reported a similar ratio ($Nqc/Nqp \approx 4$) from their study of laminar flow structure in a stirred tank agitated by a radial flow impeller.

Dong *et al.* [13] used LDA to study turbulent flow in an unbaffled tank agitated by a paddle impeller (radial flow). In particular, they investigated the effects of the impeller rotational speed and clearance to tank bottom on flow characteristics. They found that *Nqp* was independent of the impeller speed but strongly affected by the impeller clearance and was about 0.62. They also reported *Nqc*=2.0, which was found to be independent of impeller speed and off-bottom clearance. From the above findings the ratio *Nqc*/*Nqp* was about 3.2, which is lower than the value of 4 reported by other researchers. A good comparison, though, would require that the same type of agitator be used in the two studies, which was not the case. The main finding of Dong and co-workers was that the impeller clearance to the tank bottom had an effect on the pumping capacity; however it did not influence the circulation capacity of flow in the vertical plane.

A plain disk is the simplest of all mixing vessel agitators in terms of design and manufacture. It is classified as a high velocity and low flow impeller. The type of flow generated by the plain disk is mainly radial. It can be operated at high peripheral speeds with relatively low power consumption, but has poor circulating capacity and can be expected to perform well only at very low viscosities. This type of agitator is not popular because most industrial applications involve turbulent mixing and as a result only scanty publications have reported about its performance. Although it is generally perceived that turbulent mixing is the most efficient, there are several industrial applications for which it is detrimental. For instance in mixing processes where the fluid is very viscous or contains substances that are shear sensitive, turbulent agitation would lead to unfavourable mixing conditions. This research has been motivated by the fact that in some applications, as described above, a solid disk rotor would be more relevant than a bladed impeller. Bladed impellers represent too rapid a change of geometry in the flow, which leads to turbulence and higher shear rates. A solid disk rotor is thought to have the ability of producing a smoother mixing laminar flow at much higher Reynolds numbers (*Re*) compared to a bladed impeller.

A plain disk agitator has been found to function like a radial flow impeller, at least from then flow pattern point of view [14]. Nagata *et al.*'s [15] work with a rotating disk (D/T=0.513 and W/T=0.1) in an unbaffled vessel found that *Nqp*=0.031, which was very close to theoretical value of 0.027. The above impeller performance values for a plain disk are of an order of magnitude smaller than the one for a typical radial flow impeller.

Recently, Deglon *et al.* [16] investigated the efficacy of a spinning disk as a bubble break-up device. They claimed, without elaborating, that the high-speed spinning disk had achieved success in the field of mineral floatation. In their study, the spinning disk was compared with a Rushton turbine with respect to mean and turbulent velocities, turbulent energy dissipation rates and 1D turbulent energy spectra. Their preliminary results indicated that though the spinning disk impeller was found to be a less efficient device for bubble break-up than the Rushton turbine, this situation could be rectified by using spinning-disks of different dimensions and varying the operating conditions

The present research uses the plain disk agitator to describe in relatively more detail important mixing parameters such as discharge flow rate and circulation flow rate as well as their respective non-dimensional quantities. Since no previous investigator has attempted to examine the effect of agitator speed (or *Re*) and size and off-bottom clearance on the above global mixing parameters and flow patterns for a mixing vessel agitated by a plain disk the present work has endeavoured to extend knowledge in this area. Two different agitator sizes are used with one configuration similar to what was used in Nagata's [15] experimental work, for validation purpose.

NUMERICAL METHOD

The pre-processor software package Gambit was used to create a model ready for use in the CFD simulation environment. The creation of the model involved designing the geometry, meshing the model and specifying zones types in the model.

The mixing vessel configuration (Fig. 1) had an aspect ratio of 1.0 (H=T). Two different agitators were used: a smaller impeller had a diameter D=0.325T, width W=0.064T. Different models were generated using this agitator by varying its axial location along the shaft (C=0.50T, 0.35T, 0.25T and 0.15T). A bigger disk was designed to correspond with the one used by Nagata [15] partly in order to duplicate some of his results. The disk parameters were D=0.513T, W=0.10T and C=0.50T.

Because of the model symmetrical shape only one half was modelled and meshed, with an added advantage of simplifying the computational effort. The original grid was made of 77 cells in the radial direction (r) and 150 cells in the axial direction (z) resulting in a total of 11,130 cells. With a view to obtaining grid independent solutions the grid was refined further and a 22,148 cell grid was used for laminar cases. Further grid adaptation based velocity gradient was used producing 81,115 cell grid.

The grid was imported from Gambit to commercial CFD software called Fluent. The simulation fluid used was Silicone Fluid with a viscosity of 500 centistokes, a density of 969 kg/m^3. The shaft and disk surfaces were assigned a moving wall boundary condition with a defined absolute motion and no slip shear condition. The cylindrical tank wall, the tank bottom and top lid were treated as stationary walls with no slip shear condition. The continuity and momentum transport equations were solver using a commercial CFD software Fluent (versions 5.5.14 and 6.0). For turbulent cases (Re>10 000) the Reynolds Stress Model was used to solve for Reynolds stresses in addition to k (turbulence kinetic energy) and ε (turbulence dissipation rate). Transitional flow cases ($1000<Re<2000$) were solved by employing the Low Reynolds k-ε model from the turbulence-expert menu.

Post-processing was carried out using Fluent's post-processor primarily for qualitative examination of flow patterns. Quantitative examinations of simulation results were effected using an in-house software written in Matlab code and later converted to "*C*" code to improve the processing speed.

RESULTS AND DISCUSSION

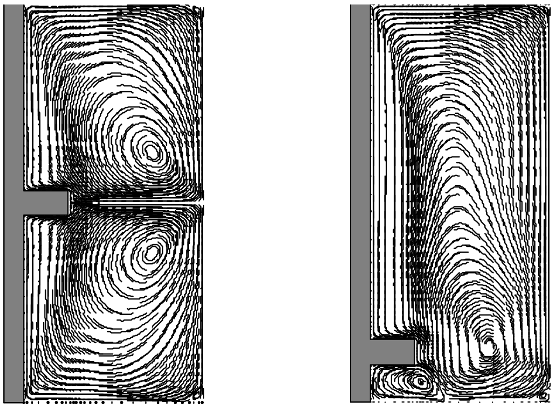
The results presented and discussed in this section are for numerical simulations of a mixing tank model (Figure 2) in different configurations using two disk sizes and various off-bottom agitator clearances. The configurations studied were:

i) <u>smaller disk</u> (*D*=0.325*T*): the clearance *C* was varied as 0.50T, 0.35T, 0.25*T* and 0.15*T* (abbreviated as C05, C035, C025 and C015 respectively);

ii) <u>bigger disk</u> (*D*=0.513*T*): only one clearance was investigated, *C*=0.50. This configuration is similar to what Nagata [15] used.

The simulations covered these *Re*: 20, 50, 75, 100, 125, 150, 200, 300, 500, 750, 1000, 1250, 1500, 1750, 2000, 10000 and 50000. However, not all *Re* were covered in each case.

Fig. 3 shows the flow patterns generated by the agitator's action on the liquid in the mixing vessel. In the case of the centrally located disk (Figure 3a) the two recirculation zones, above and below the impeller, are identical due to the symmetry of the model. In Figure 3b, where the impeller is much closer to the tank bottom, the flow is not symmetrical, and the upper recirculation region extends beyond the disk to occupy a significant portion of the bottom region. The pumping jet emanating from the disk is no longer purely radial but is inclined at an angle of approximately 45° with respect to the horizontal plane cutting through the middle of the disk. This behaviour has been reported by other researchers using baffled tanks agitated by radial flow impellers [17-19]. Using a radial flow impeller, Montante *et al.* [19] found that at an impeller clearance *C* = 0.20*T* the characteristic double-loop flow pattern undergoes a transition to a single-loop pattern with the impeller stream direction becoming partly axial and inclined at around 25° to 30° to the horizontal.

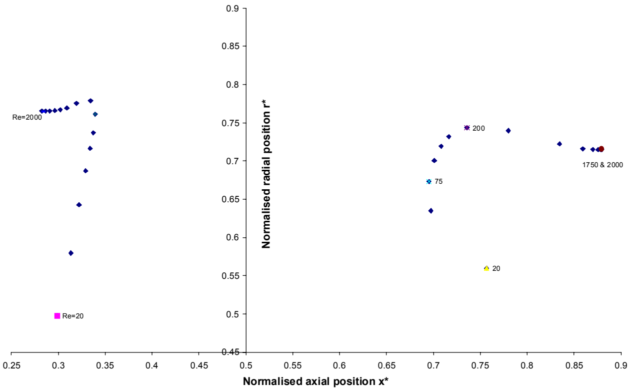


a) *C*=0.50*T* (*Re* = 300) b) *C* = 0.15 (*Re* = 200)

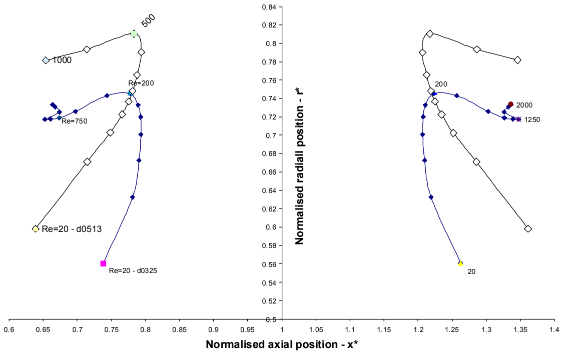
Figure 3: Pathlines: upper and lower recirculations (axial and radial distances are in "m").

At low *Re* it has been shown that there exist segregated mixing regions, also known as Isolated Mmixing Regions or *IMR*, in the form of toroidal vortices above and below an impeller [20, 21]. These regions have been observed not to easily exchange material with surrounding zones where active mixing takes place. This lack of material exchange is perhaps the main reason why laminar mixing is thought to be inefficient.

An important step in understanding the behaviour of the *IMRs* is to be able to predict their movement under different mixing conditions (Figures 4a & 4b). Makino *et al.* [21] showed that the centres of these *IMRs*, correspond to the centre of the recirculation regions as illustrated in this work. They examined the movement of the centres of the IMR and found that it was shifting outwards, in other words away from the impeller tip towards the tank cylindrical wall. The same tendency was observed by Lamberto *et al.* [12]. This work extends the above studies and that of Mununga *et al.* [14] by covering a wide range of *Re* and different configurations as explained above.



a) Small disk (*d*0325) with *C* = 0.25*T*



b) Small disk (*d*0325) and big disk (*d*0513) with *C* = 0.50*T*:

Figure 4: Locus of the centre of recirculation regions (*LHS*: lower region and *RHS*: upper region)

<u>*Circulation flow*</u>

Figures 4a and b show the loci of the centre of recirculation regions (or centre of *IMR*) for different *Re*. The axial and radial positions are normalised with respect to the tank radius (*T*/2). Figure 4a is for the small disk (*d*0325) at a clearance of *C*=0.25*T*. It is evident that the two loci are different due to the asymmetry of the geometry. The two centres of IMR exhibit the same trend: initially moving radially away from the impeller or axis of rotation (horizontal axis), as described by previous researchers [12]. What other researchers did not observe was that the centres tend to move closer to impeller in the axial direction. The two motions continue until a saturation point is reached, thereafter the motion of the centres reverses in both directions: moving radially towards the axis of rotation and axially away from impeller.

In Figure 4b, the loci of the centres of recirculation for the small (*d*0325) and big (*d*0513) disks operating at C=0.50T are compared. It can be seen that the general motion of the centres is as explained above (Figure 4a). The loci for the lower and upper centres are identical, which implies that up to a *Re*=2000 the flow is still symmetrical or stable, which agrees with the observations of Gelfgat *et al.* [22] and Hourigan *et al.* [23]. The locus of the centre of the bigger disk appears shifted, mainly in the radial direction compared to that for the smaller disk. It follows, therefore, that the positions of the *IMRs* depend on the rotational speed, size and location of the impeller.

The location of the centre of recirculation is of critical importance in computing the values of circulation flow rate (Equations 5 and 6). Figure 5 shows the effect of *Re* on the circulation flow rate (*Qc*) for different configurations. There appears to be a linear relationship between the circulation flow rate, *Qc*, and *Re*, except for the deviation observed after *Re*=1250 (*C*05). So far, there is no explanation for the deviation except that further simulations and experiments will have to be conducted to gain more insight. Of particular importance is the fact that the circulation flow rate curves for *C*050, 035 and 025 almost merge into a single line and lie above those corresponding to *C*015 (small disk) and *C*050 (big disk). From the above results it appears that circulation flow rate is not sensitive to the change of clearance for $0.25T<C<0.50T$ but is significantly decreased when the clearance is further reduced ($C < 0.15T$). This means that smaller impeller clearances, although useful for transitional flow from double loop to single loop [10, 24] are damaging to the net circulation flow rate.

The variation of the circulation flow number, *Nqc*, with *Re* is shown in Figure 6, which is a direct product from Fgure 5, and as such it is not surprising that similar trends can be observed. The important feature to note here is that in the laminar flow regime (*Re*<300) *Nqc* is not constant. The value of *Nqc* appeared to stabilise after *Re*=300, up to the transition region. From results not shown here it appeared that in the turbulent region there seemed to be a decrease in *Nqc*. The circulation numbers for *C*050, 035, 025 and 015 seem to be similar, about 1.2± 0.05 and above those for *C*015 and at least *Re*=300 through to the transition region. The values of *Nqc* found here are about three times (small disk) and an order of magnitude (big disk) smaller than the ones for radial flow impellers.

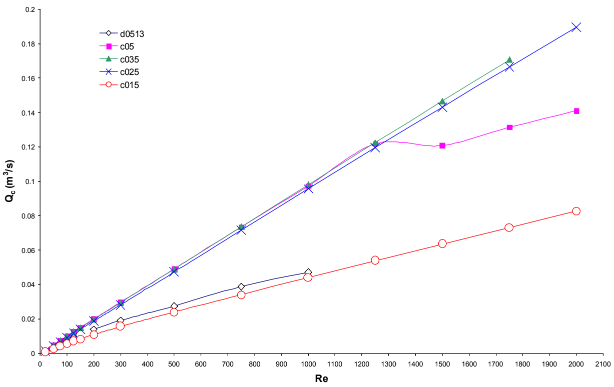


Figure 5: Circulation flow rate vs *Re*

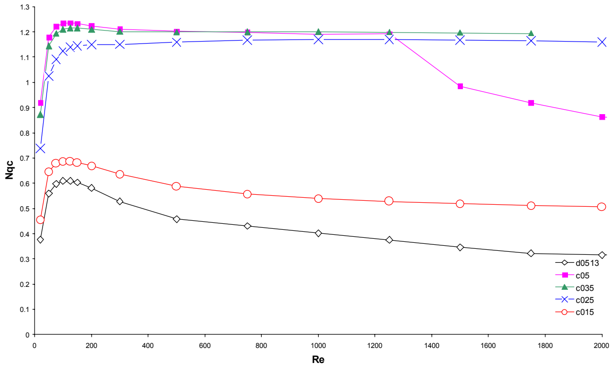


Figure 6: Circulation flow number vs *Re*

Discharge flow rate

The discharge flow rate (*Qp*) was seen to be varying in the radial direction as shown in Figure7. A maximum value can be observed at a radial position between the tip of the disk and the tank wall. As noted by Revill [25] there are numerous ways researchers have used to define pumping flow rate. Because of the lack of a commonly acceptable definition values of published *Qp* an *Nqp* are often different. Nagata's [15] experimental result for a solid disk, similar to the big disk used here, was used to validate the computations. From the above result it was established that *Qp* was calculated at 1.3% of T away from the impeller tip in order to avoid excessive amount of induced flow from the lower and upper recirculation regions.

In Figure 8 a comparison of the discharge flow rates for the four configurations at various *Re* is presented. In all the configurations the discharge flow rate is seen to increase almost linearly with corresponding increases in *Re*. The bigger disk's discharge flow rates are the highest and the smallest values are those for the small disk with the smallest clearance (C=0.15T). Once again, the flow rates for the small disk at C=0.50T, 0.35T and 0.25T are almost identical as they appear to merge. This seems to suggest that the above three clearance values are equally effective with respect to pumping flow and circulation flow (as shown earlier). It is evident that the size of the agitator affects the discharge flow rate. In addition, a smaller clearance ($C \leq 0.15T$) value reduces the amount of discharge.

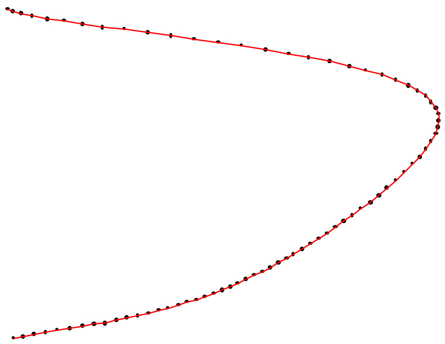


Figure 7: Variation of *Qpmax* with radial location

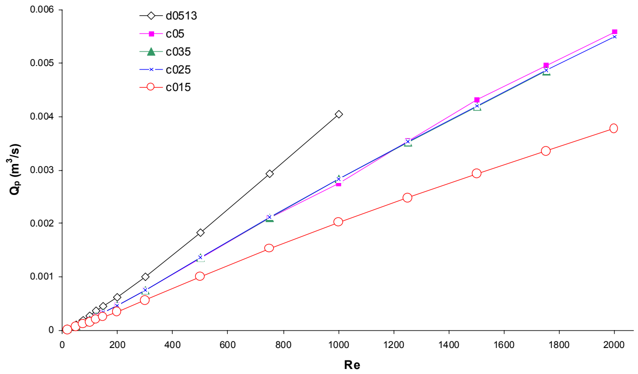


Figure 8: Discharge flow rate vs *Re*

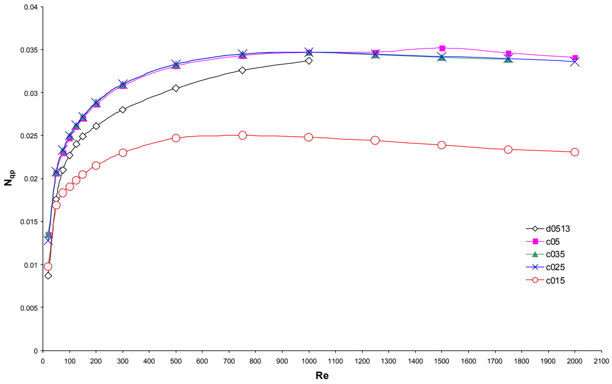


Figure 9: Discharge flow number vs *Re*

The variation of the non-dimensional discharge flow numbers (*Nqp*) with *Re* is shown in Figure 9 for all the four configurations. The general trend, for $20 \leqslant Re \leqslant 2000$, is in agreement with Nagata's [4] results for unbaffled tanks agitated by an 8-blade paddle. The *Nqp* seems very low for lower *Re* and increases as the *Re* is augmented until it reaches what appears to be a maximum ($500<Re<1000$). In the transition region, $Re>1000$, the *Nqp* is fairly constant with a value of about 0.034. Nagata [4] reported the value *Nqp*=0.031 from his experimental work for a turbulent flow case and a theoretical value of 0.027. The predicted *Nqp* value in this work was 0.034 (for both disks) in the transition region while in the turbulent region it dropped to about 0.024 for the small disk, which is reasonably close to the theoretical value. For the big disk *Nqp* was fairly constant, but with a slight decrease, from the transition region to the turbulent region. In the fully turbulent region (*Re*=50 000) *Nqp*=0.016. It appears that the discharge flow number is independent of the size of the agitator, in accordance with Revill's [25] findings. The dependence of *Nqp* with *Re* and *C* has been a subject of controversy; what this work has shown is that *Nqp* is not constant over the entire range of *Re*, although it seems constant in the transition region, about 0.034, and slightly dropping in value within the turbulent region to about 0.024. Once again the smaller clearance configuration exhibits the lowest values of *Nqp*. This seems to suggest that excessive reduction of impeller clearance has an adverse effect on the discharge flow characteristics. This trend confirms the findings of Nagata [4]. It is worth noting that the reduction of *C* to values less than 0.15*T* causes a significant reduction in power consumption [10]. The values of discharge number are of an order of magnitude smaller than the ones for radial flow impellers, this indicates that the plain disk has a relatively poor pumping capacity.

CONCLUSIONS

The motion of the centre of recirculation, the circulation and discharge flow rates and their respective non-dimensional numbers have been investigated for a mixing tank agitated by a plain disk. The locus of the recirculation centre has been found to follow a general trend, initially moving radially away from the axis of rotation but axially closer to the impeller mid plane. After going through a turning point the centre of recirculation moves in the reverse direction. Knowledge of this motion will help researchers to understand the motion of the Isolated Mixing Regions (*IMR*) commonly present in laminar mixing.

Circulation flow rate was observed to be linearly dependent on the *Re* and also on the disk size: the bigger the size of the agitator the lower the value of *Nqc*. The range of clearance values, $0.25 \leq C \leq 0.50$, has been seen to produce the same discharge and circulation flow rates for the same disk size. A smaller clearance $C = 0.15T$ has been shown to impair circulation and discharge flow rates, *Nqc* and *Nqp*.

The discharge flow rate was seen to be dependent on both the *Re* and the disk size. Unlike in the case of *Nqc*, *Nqp* increases as the disk size is enlarged. The values of *Nqc* and *Nqp* found here are smaller than the ones for radial flow impellers.

Both the circulation and discharge flow numbers appear not to be constant over the "entire" range of *Re*, from laminar to turbulent, but they seem to be in the transition region. It is hoped that more work in the fully turbulent region will reveal that theses values will be constant again at a lower level.

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