Particle Dispersion and Fluid-Particle Interaction in a Slurry of Liquid Al–Mg Alloy and Al₂O₃ Particles

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The influence of process parameters such as the temperature, stirring speed and position of the impeller and its size on the flow pattern of molten Al–4 mass% Mg alloy controlling the retention of Al₂O₃ particles in it has been analysed. The analysis of the mixing process was carried out with the help of a model expression for the various parameters of a concentrically agitated fluid system influencing the fluid profile at the top of the crucible. The results show that in all the choices of process parameters in this work the impeller surface has been exposed except during mixing at the holding temperature of 883 K. The exposing of the impeller has been found to play a significant role in retaining the particles in the agitated slurry. However, the retention of particles has been found to be controlled by the radius of the cylindrically rotating zone, \( r_c \), which increases with the increase in the stirring speed and size of the impeller at a given holding temperature. The retention of particles in the slurry increases so long as \( r_c \) remains below \( r_s \), the radius of the central region of the impeller excluding the blades. In case of low holding temperature of 883 K a large retention of alumina inside the melt without any exposure of the impeller may have been possible due to the mechanical entrapment of the particles. The observations of cold model experiments have been found to be in qualitative agreement with the results obtained in the cast composites.

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I. Introduction

The incorporation of non-metallic particulate materials through the vortex formed at the surface of the vigorously agitated partially solid alloys known as compocasting has been found\(^1\) as an effective process for making particulate composites\(^2\). It has been observed that in the compocasting process the variation in the mixing parameters such as the holding temperature of the melt, stirring speed, and the position and size of the impeller affects the particle retention in the composite to a great extent\(^2\). It has also been observed that in the vortex method of fabrication of a cast particulate composite the extent of particle incorporation affects the porosity content of the composite which influences the mechanical properties of the composite at ambient and elevated temperatures\(^3\)–\(^6\). However, no study has been carried out so far to understand the influence of these mixing parameters on the flow pattern of a concentrically agitated partially solid melt affecting the retention of ceramic particles in it. In an earlier study of a concentrically agitated liquid system\(^6\) it has been observed that the radius of cylindrically rotating zone, \( r_c \), formed in the forced vortex region of an agitated liquid is having a considerable influence on its flow pattern and the sucking action at the vortex. The \( r_s \) has been found to vary with the variation in mixing parameters such as the stirring speed, the size of the impeller and the viscosity of the liquid.

In this investigation an effort has been made to analyse the mixing process during fabrication of particulate composite by the compocasting process while the mixing parameters are varied. The analysis has been carried out with the help of a model expression correlating the various parameters and the fluid profile
at the top of the slurry in a concentrically agitated fluid system. In addition the qualitative knowledge gained from the cold model experiment reported earlier has also helped to understand the behaviour of particle retention in the slurry under various conditions of mixing.

II. Experimental

To study the impact of mixing parameters on the amount of incorporation and distribution of alumina particles in Al-4 mass% Mg-Al₂O₃ cast composite the process variables are stirring speed, size of the impeller, its position inside the melt and the holding temperature of the melt. The stirring speed measured with the help of a strobometer is varied from 7.5 to 25 revolutions/s. The size of flat four blade impeller as described in part I and used also in this investigation, is expressed as the ratio of \( d/D \) where \( d \) is the diameter of the impeller and \( D \) is the surface diameter of the melt at rest having the stirrer dipped in to it. The value of \( d/D \) is varied from 0.56 to 0.74. The position of the impeller inside the melt expressed as the dimensionless height ratio \( h/H \) is varied from 0.54 to 0.91, where \( h \) is height of the impeller from the bottom of the crucible and \( H \) is the depth of the melt at rest having stirrer dipped. The holding temperature of the melt is varied from 883 to 958 K and has been measured with the help of a potentiometer connected to the thermocouple dipped at a depth of 15-20 mm from the top fluid surface.

About 500g of commercially pure aluminium is melted in a crucible having a bottom pouring arrangement placed inside an electrically heating muffle furnace as shown in Fig. 1 and heated up to 1005 K. The molten aluminium is alloyed by inoculation of magnesium in it at a suitable temperature just before stirring the melt. The melt is agitated vigorously at different speeds as required. The temperature of the furnace is allowed to drop slowly until the melt reaches the desired holding temperature. About 40g of alumina particles approximately round in shape (Fig. 2) with the size range in Table 1 preheated to 1072 K are added from the top to the vortex formed on the melt surface at the rate of 1.66-2.5 g/s. Stirring is continued for 225-240 s after the addition of particles to the melt. During this period the temperature of the slurry is kept within ±5 K of the holding temperature. The slurry is poured in a 25 mm × 30 mm × 300 mm steel mould by removing the graphite stopper from the bottom of the crucible, and the ingot is quenched immediately.
with spraying water. During pouring the stirring is continued.

Suitable metallographic samples are prepared from both the bottom and the top of each casting by using a standard metallographic procedure. The specimens are observed under an optical microscope for estimation of the particle content of the composite. The volume fraction of alumina particles in each specimen is determined by using observed density and the point counting method\(^2\).

### III. Results

The effects of the holding temperature, stirring speed, and the position and size of the impeller on the variation in retention of alumina particles at the bottom and the top of the cast composites are shown in Table 2. The retention of alumina particles at the bottom and the top of the ingot have been studied to assess the homogeneity of alumina particle distribution in the slurry during mixing. It has been presumed that the liquid-solid interface movement is so fast in the mould that the particle distribution is not significantly altered during solidifica-

| Stirring speed (r.p.s.) | Size of impeller \((d/D)\) | Position of impeller \(h/H\) | Holding temperature \((K)\) | Bottom of the ingot (mass%) | Top of the ingot (mass%) |
|------------------------|----------------------------|-----------------------------|---------------------------|-----------------------------|--------------------------|
| 7.5                    | 0.63                       | 0.81                        | 900                       | 1.8                         | 3.2                       |
| 9.7                    | 0.63                       | 0.81                        | 900                       | 3.0                         | 4.4                       |
| 16.0                   | 0.63                       | 0.81                        | 900                       | 12.8                        | 12.6                      |
| 19.2                   | 0.63                       | 0.81                        | 900                       | 10.8                        | 12.8                      |
| 22.5                   | 0.63                       | 0.81                        | 900                       | 9.9                         | 9.5                       |
| 25.0                   | 0.63                       | 0.81                        | 900                       | 1.9                         | 2.5                       |
| 16.0                   | 0.56                       | 0.81                        | 900                       | 3.5                         | 2.8                       |
| 16.0                   | 0.59                       | 0.81                        | 900                       | 6.4                         | 6.2                       |
| 16.0                   | 0.63                       | 0.81                        | 900                       | 12.8                        | 12.6                      |
| 16.0                   | 0.71                       | 0.81                        | 900                       | 4.6                         | 3.9                       |
| 16.0                   | 0.725                      | 0.81                        | 900                       | 1.6                         | 2.9                       |
| 16.0                   | 0.74                       | 0.81                        | 900                       | 1.2                         | 3.1                       |
| 16.0                   | 0.63                       | 0.54                        | 900                       | 1.8                         | 4.2                       |
| 16.0                   | 0.63                       | 0.67                        | 900                       | 7.4                         | 10.2                      |
| 16.0                   | 0.63                       | 0.74                        | 900                       | 11.2                        | 12.7                      |
| 16.0                   | 0.63                       | 0.81                        | 900                       | 12.8                        | 12.6                      |
| 16.0                   | 0.63                       | 0.87                        | 900                       | 9.3                         | 9.9                       |
| 16.0                   | 0.63                       | 0.91                        | 900                       | 5.0                         | 8.8                       |
| 16.0                   | 0.63                       | 0.81                        | 883                       | 19.9                        | 21.4                      |
| 16.0                   | 0.63                       | 0.81                        | 900                       | 12.8                        | 12.6                      |
| 16.0                   | 0.63                       | 0.81                        | 930                       | 6.9                         | 8.5                       |
| 16.0                   | 0.63                       | 0.81                        | 958                       | 8.2                         | 8.4                       |
The particle retained in the ingot is found more than the amount of particle added because of extensive oxidation in stirred melt. Table 2 shows that a relatively higher amount of alumina is retained in the casting at a holding temperature of 883 K as shown in the micrographs shown in Fig. 3(a) and (b) representing the bottom and the top of the ingot respectively. At this temperature the retention of alumina at the bottom of the casting has been found to be comparatively less than that at the top of the casting. The increase in holding temperature of the slurry within the range of the solidus (875 K) and the liquidus (915 K) temperature of Al–4.0 mass% Mg alloy drastically reduces the retention of alumina particles in the castings. However, at the holding temperature of 900 K no significant difference in alumina content between the bottom and the top of the casting is observed (Table 2) as revealed in the micrographs shown in Fig. 3 (a) and (b) respectively. The increase in holding temperature in the region beyond the liquidus point of the alloy does not affect significantly the retention of alumina particles in the casting as shown in Table 2.

In spite of the significant role of a lower holding temperature (883 K) in the retention of alumina in the castings the investigations on the effects of the stirring speed and the size and position of the impeller on the retention of alumina in the castings have been carried out at 900 K because at a lower holding temperature the pouring of the slurry often become difficult due to choking at the bottom hole of the crucible. During the variation of stirring speed at given parameters of $d/D=0.63$ and $h/H=0.81$ a small amount of alumina has been retained in the casting a major part of which exists at the top of the ingot when the stirring speed is kept at 7.5 revolution.s$^{-1}$ (Table 2). However, the table shows that the retention of alumina increases with the increase of stirring speed reaching to a maximum with no significant difference between the bottom and the top of the ingot at 16 revolution.s$^{-1}$ followed by a reduction of it with a further increase in stirring speed upto 25 revolution.s$^{-1}$. At the stirring speed of 23 revolution.s$^{-1}$ a considerable clustering of alumina particles at the top of the ingot has been marked in Fig. 5 and at 25 revolution.s$^{-1}$ the retention although small has been observed primarily at the top of the casting as revealed in Table 2.

The influence of the position of the impeller ($h/H$) indicates (Table 2) that the retention of alumina in the castings increases with an increase in $h/H$ till $h/H=0.81$ followed by a decrease with a further increase in $h/H$ when the stirring speed and the size of the impeller has been maintained at 16 revolution.s$^{-1}$ and 0.63 respectively. It has also been marked that at both the lowest and highest $h/H$ of 0.54 and 0.91 respectively the alumina is retained significantly more at the top of the casting than

![Fig. 3](image_url) 

**Fig. 3** Micrographs showing the retention of alumina particles (a) at the bottom and (b) at the top of the casting made at the holding temperature of 883 K, stirring speed of 16 revolution.s$^{-1}$, $d/D=0.63$, $h/H=0.81$. 
that retained in its bottom with a tendency of clustering at the top of them as shown in Fig. 6(a) and (b) respectively. However, at $h/H=0.81$ no significant difference in the retention of alumina exist at the top and the bottom of the casting.

At a given stirring speed of 16 revolution.s$^{-1}$ and $h/H=0.81$ the retention of alumina in the casting increases with an increase in the size of the impeller upto $d/D=0.63$ followed by a sharp fall with a further increase in $d/D$ as shown in Table 2. At $d/D=0.63$ the difference in retention of alumina between the top and the bottom of the castings exists when $d/D$ is kept at 0.56 and 0.74 with a larger difference in later case having a higher retention at the top.

### IV. Discussion

The height of the surface of the melt at rest from the bottom of the crucible, $H$, can be estimated in terms of volume of the melt, $V$, and the radius of the crucible, $r_2$, as

$$H = \frac{V}{\pi r_2^2}$$  \hspace{1cm} (1)

Now, the volume of the melt during stirring can be expressed\(^\text{6}\) as

$$V = Z_0 \pi r_2^2 + \pi (\omega^2/4g) r_4^2 + \pi (\omega^2/g) r_3^2 (r_2 - r_3^2)
 - \pi (\omega^2 r_4^2 / g) \ln (r_2 / r_3),$$  \hspace{1cm} (2)

where, $Z_0$ is the height of the lowest point of the top fluid profile at vortex from the bottom of the crucible. By substituting the eq. (2) in (1) one gets

$$\frac{(H-Z_0)}{r_3^2} (g/\omega^2)
 = y^2 - y^4 (2.303 \log (1/y) + 0.75),$$  \hspace{1cm} (3)

where,

$$y = r_c / r_2 \leq 1,$$  \hspace{1cm} (4)

The value of $\omega$ is estimated as

$$\omega = 2n\pi,$$  \hspace{1cm} (5)

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**Fig. 4** Micrographs showing the retention of alumina particles (a) at the bottom and (b) at the top of the casting made at the holding temperature of 900 K, stirring speed of 16 revolution.s$^{-1}$, $d/D=0.63$, $h/H=0.81$.

**Fig. 5** Micrograph showing a considerable clustering of alumina particles at the top of the casting made at the holding temperature of 900 K, stirring speed of 23 revolution.s$^{-1}$, $d/D=0.63$ and $h/H=0.81$. 

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The value of $\omega$ is estimated as $\omega = 2n\pi$. 

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where, \( n \) is the stirring speed expressed in \( \text{revolution.s}^{-1} \). The value of \( r_c \) is estimated from the expression\(^6\)

\[
\frac{r_c}{r_1} = \frac{Re}{(10^3 + 1.6 Re)}, \quad (6)
\]

where, \( r_1 \) is the radius of the impeller and \( Re \) is the Reynold’s number of the agitated slurry estimated as

\[
Re = \frac{d^2 n \rho_{\text{slurry}}}{\eta_{\text{slurry}}}, \quad (7)
\]

where, \( \rho_{\text{slurry}} \) and \( \eta_{\text{slurry}} \) are the average density and the coefficient of viscosity of the partially solid Al-4 mass\% Mg alloy respectively. The value of \( \eta_{\text{slurry}} \) is evaluated\(^8\) as

\[
\eta_{\text{slurry}} = \eta_L [1 + 2.5 \phi + 10.05 \phi^2 + 0.00273 \exp(16.6 \phi)], \quad (8)
\]

where, \( \eta_L \) is the coefficient of viscosity of the liquid component of partially solid melt. The value of \( \rho_{\text{slurry}} \) is estimated\(^9\) as

\[
\rho_{\text{slurry}} = \phi \rho_S + (1 - \phi) \rho_L, \quad (9)
\]

where, \( \phi \) is the volume fraction of \( \alpha \)-solid particles in the slurry, \( \rho_S \) is the density of the \( \alpha \)-solid particles and \( \rho_L \) is the density of the liquid component of the slurry. The value of \( \phi \) in partially solid Al-4 mass\% Mg alloy has been estimated by well known Scheil’s equation\(^10\) as

\[
C_s = K_0 C_0 (1 - \phi)^{K_0 - 1}, \quad (10)
\]

where \( K_0 \) is the partition ratio of the solute expressed as \( K_0 = C_s / C_L \), \( C_o \) is the magnesium content in the alloy. \( C_s \) and \( C_L \) are the magnesium content in the solid and in the liquid respectively at a given temperature within the partially solid range of the alloy.

For the condition when the vortex has just touched the surface of the impeller one puts \( Z_0 = h \) in eq. (3), to get

\[
\left\{ \frac{(H-h)}{r_2^2} \right\} \frac{g}{\omega^2} = y_2 - y_4 [2.303 \log (1/y) + 0.75]. \quad (11)
\]

The right and left hand side expressions of the eq. (11) are denoted as \( f_1 \) and \( f_2 \) respectively. Now from the values of \( f_1 \) and \( f_2 \) for the variation of the stirring speed, \( n \), one gets the graphical solution of the stirring speed where the impeller gets exposed under a given condition of mixing. Figure 7 shows the graphical solution for the critical speed at which the impeller of various sizes get exposed and Fig. 8 shows the solution for the critical speeds for different positions of the impeller inside the partially solid melt. It has been observed that in all cases the impellers have been exposed at the high speed of stirring (16 revolution.s\(^{-1}\)) used in the present investigation. So the range of our investigation falls within the effective limits indicated by the cold model experiments reported earlier\(^7\) in respect of exposing the stirrer for effective incorporation. Figure 9 shows that the impeller has been exposed at the stirring speed of 16 revolution.s\(^{-1}\) when the
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The holding temperature of the melt has been kept at 900 K but when the holding temperature is reduced to 883 K, at the same stirring speed, the stirrer remains inside the melt as a result of an increase in viscosity, \( \eta_{\text{slurry}} \), by the solid phase in the melt. In the ingots prepared in this investigation the alumina particles retained consist of the powder added and the oxides formed due to oxidation on the surfaces of the sucked bubbles. Since the bubbles and the particles sucked through vortex are proportional and controlled by the vortex condition the total particle retained is still determined by the process variables.

While investigating the effect of holding temperature on the retention of alumina particles in the casting it has been estimated from eq. (10) that at the holding temperatures of 883 and 900 K the Al-4 mass% Mg slurry contains about 78% and 57% \( \alpha \)-solid particles respectively. During the addition of alumina particles in a vigorously agitated partially solid aluminium alloy melt the added particles collide with the particles of the primary solid phase imparting kinetic energy and momentum in random directions. The residence time of the alumina particles in the slurry is enhanced due to successive collisions. Thus the incorporation of these particles in the slurry is increased giving rise to a better mixing. Though at the holding temperature of 883 K the impeller has not exposed during stirring with a speed of 16 revolution.s⁻¹ (Fig. 9) yet the increase in retention of the alumina particles in the slurry at this holding temperature is observed as shown in Table 2 and revealed in the micrographs presented in Fig. 3(a) and (b).

Enhanced incorporation of alumina particles in two phase slurries has also been observed by a number of workers. With increasing holding temperature to 900 K the amount of \( \alpha \)-solid particles in the slurry falls down and the retention of alumina particles in the composite also become less (Table 2) as revealed in the micrographs presented in Fig. 4(a) and (b). The decrease in the amount of alumina reten-
tion in the casting with an increase in the holding temperature clearly establishes the significant role of proeutectic $\alpha$-solid in the slurry whose amount decreases with increasing holding temperature. At a holding temperature beyond the liquidus point of the alloy ($915\,K$) no $\alpha$-solid particles occurs. Thus at a holding temperature beyond $915\,K$ a comparatively lower retention of alumina particles is observed in the casting as shown in Table 2 and the variation in holding temperature in this range does not significantly influence the amount of retention of alumina particles.

At a holding temperature of $900\,K$ no significant difference exists between the alumina contents at the bottom and the top of the casting as shown in Table 2 and Fig. 4(a) and (b) which is in agreement to the earlier observation regarding the effectiveness of lowering the holding temperature in achieving a better distribution of alumina in aluminium alloy. However, at a holding temperature of $883\,K$ the slurry has an $\alpha$-solid particles content as high as $78\%$, there is a difference of about $1.5\%$ in the retention of alumina between the bottom and the top of the casting. The difference in the particle distribution at the top and the bottom of the castings should depend on the extent of particle incorporation and the motion of the particles after collisions. If the particle content is large the random collisions may not be able to disperse the colliding particles to a larger distance and the distribution may become poor. A higher viscosity of the slurry also affects the distribution by restricting the flow of the slurry. This may be the reason for observing a larger segregation of the particles between the top and the bottom of an ingot cast at a holding temperature of $883\,K$ compared to that at $900\,K$ although the particle retention is higher in the case of holding at $883\,K$.

At the holding temperature of $900\,K$, the size ($d/D=0.63$) and position ($h/H=0.81$) of the impeller the annular flow of the liquid under the secondary circulation touches the higher region of the vortex with increasing stirring speed\textsuperscript{14}. It may be noted that the particles fall at the centre as well as all along the surface of the vortex during the addition of the alumina particles from the top in the vortex. The annular flow provides a substantial down flow of the slurry from the higher region of the vortex and it drags alumina particles lying on the surface of the vortex along with slurry towards the impeller. An increase in the stirring speed enhances this annular flow resulting in an increase in the retention of alumina inside the slurry as shown in Table 2 when the stirring speed is increased from 7.5 to 16 revolution$^{-1}$. The radius of the cylindrically rotating zone, $r_c$, increases with increasing stirring speed and up to the stirring speed of 16 revolution$^{-1}$ the value of $r_c$ remains lower than the value of $r_5=15.25\,mm$ for $d/D=0.63$. But with a further increase of stirring speed the value of $r_c$ exceeds the value of $r_5$ as shown in Fig. 10 and results in the suction of air bubbles as reported earlier. The alumina particles entering with an air envelope cannot be wetted by the slurry and are accumulated at the bottom of the impeller resulting in a reduction in the retention of particles at a stirring speed beyond 16 revolution$^{-1}$ as shown in Table 2. The clustering of alumina particles at the top of the ingot cast from a slurry stirred at
23 revolution.s$^{-1}$ is shown in Fig. 5. This result is in agreement with the observed accumulation of particles at the bottom of the impeller in cold model experiment$^{(7)}$. However, that a further increase of the stirring speed to 25 revolution.s$^{-1}$ has drastically reduced the retention of the particles in the casting (Table 2) may be due to the enhanced suction of air bubble and their attachment to the particles increasing the buoyancy. In Fig. 11 it is interesting to note that in the case of the holding temperature (900 K), the size of the impeller ($d/D=0.63$) and the position of the impeller ($h/H=0.81$), the retention of alumina in the composite increases as the ratio $r_c/r_1$ increases to 0.605 with increasing stirring speed from 7.5 to 16 revolution.s$^{-1}$. However, with a further increase in $r_c/r_1$ by the increase of the stirring speed from 16 to 25 revolution.s$^{-1}$ the extent of alumina retention reduces drastically. It is important to note that the difference in retention of particles between the bottom and the top of the casting is again minimum at a retention level of 12.7 mass% alumina, as revealed in Fig. 4(a) and (b).

The vertical motion of the liquid during its annular flow is largely dependent on the speed of stirring. So, under the condition of the holding temperature (900 K), the size of the impeller ($d/D=0.63$), and the stirring speed (16 revolution.s$^{-1}$), the extent of the annular flow above the impeller is fixed for a given position of the impeller. Thus under the above mentioned mixing condition, the annular flow at the vortex surface is reduced significantly when the impeller is placed at a larger depth ($h/H=0.54$) inside the slurry. As shown in Table 2 the particles lying on the fluid surface at the vortex remain confined there to a larger extent and do not enter the slurry resulting in a reduced retention of alumina in the castings when the impeller is placed at $h/H=0.54$. With the increasing value of $h/H$, the retention of particles in the casting increases up to 12.7 mass% at $h/H=0.81$ as given in Table 2 and Fig. 4, because at a higher $h/H$ ratio the depth of the vortex is decreased and thus the annular flow of the slurry is effective in drawing the particles from the surface of the vortex. However, with a further increase in the value of $h/H$ beyond 0.81, the turbulence in the vortex region becomes very large and the particles remain confined in the region of the slurry above the impeller adversely affecting the particle retention. As such the alumina content of the casting is lowered as is observed in Table 2.

Under the holding temperature of 900 K, the stirring speed of 16 revolution.s$^{-1}$ and the position of the impeller of $h/H=0.81$, the value of $r_c$ has been found to increase linearly with the increasing size of the impeller as shown in Fig. 12. From this figure it is evident that the values of $r_c$ are higher than those of $r_1$ for the impeller of $d/D=0.56$ and $d/D=0.59$. Thus, in view of the similar phenomena discussed earlier for...
the case of \( r_c > r_3 \) it can be inferred that in both of the above cases the alumina particles along with the air bubbles are accumulated at the bottom of the impeller without mixing with the slurry resulting in a reduced retention of the particles in the castings at \( d/D=0.56 \) as shown in Table 2. However, with increasing size of the impeller from \( d/D=0.56 \) to 0.59, the difference between \( r_c \) and \( r_3 \) is reduced due to the increase of \( r_c \) (Fig. 12) and as a result the retention of alumina particles in the casting is increased as shown in Table 2. The value of \( r_c \) is a little lower than the value of \( r_3 \) when the stirring of partially solid melt has been carried out by the impeller of \( d/D=0.63 \). Thus no accumulation of air bubble takes place at the bottom of the impeller and a large retention of alumina particles in the casting is obtained as shown in Table 2 and Fig. 4(a) and (b). This enhanced retention of alumina in the casting has been attributed to a significant role of the exposure of the impeller. With a further increase in size of the impeller to \( d/D=0.74 \), the difference in \( r_c \) and \( r_3 \) increases continuously having \( r_c \) always less than \( r_3 \) as shown in Fig. 12. Although \( r_c \) is lower than \( r_3 \) in the above cases, the retention of alumina has been found to decrease with increasing value of \( d/D \) as shown in Table 2. This may be attributed to the decreased volume of the liquid under turbulence with an increase in \( r_c \) and the effect of back reflection of beads from the vessel wall in the use of a large size impeller as confirmed in the cold model experiment reported earlier\(^7\).

When large impellers of \( d/D=0.72-0.74 \) are used, the retention of alumina at the top of the castings becomes considerably higher than that observed at the bottom as shown in Table 2. For the given holding temperature (900 K), the stirring speed (16 revolution.s\(^{-1}\)) and the position of the impeller (\( h/H=0.81 \)), the value of \( r_c/r_1 \) increases up to 0.605 with the increasing size of the impeller (\( d/D \)), and the amount of retention of alumina in the casting is also enhanced followed by a sharp fall with a further increase in \( r_c/r_1 \) as shown in Fig. 11. It is interesting to note that the retention of alumina is more sensitive to the ratio \( r_c/r_1 \) during the variation in impeller size (\( d/D \)) than that observed in the case of variation in stirring speed (\( n \)) (see Fig. 11).

**V. Conclusion**

Increasing the stirring speed, size and height of the impeller from the bottom of the crucible to a certain extent increases the level of retention of alumina in the composite produced by the vortex method, followed by a reduction with a further increase in the values of these process parameters. An increase in holding temperature within the partially solid range of the Al-4.0 mass% Mg alloy reduces the amount of alumina retained in the casting but a further increase beyond the liquidus temperature of the alloy does not affect it significantly. For the given design of impeller a maximum retention of alumina in the cast composites has been obtained when the process parameters are maintained at a stirring speed of 16 revolution.s\(^{-1}\), \( d/D=0.63 \) and \( h/H=0.81 \) and holding temperature of 900 K. The deviation of these parameters from the optimum values causes a significant difference in alumina retention between the top and the bottom of the ingot. The tendency to clustering of alumina particles increases with the rise in its level of retention.

Analysis of the mixing process shows that for all the choices of process parameters in this work the impeller surface has been exposed except during mixing at a holding temperature of 883 K, where a large retention of alumina in
the slurry has been observed possibly due to widespread mechanical entrapping of alumina particles by the \( \alpha \)-particles in the slurry. The radius of the cylindrically rotating zone, \( r_c \), of the slurry under a concentric stirring plays an important role in the retention of alumina particles in the slurry. The retention of particles in the slurry increases so long as \( r_c \) remains below \( r_3 \), the radius of the central region of the impeller excluding the blades, because at \( r_c > r_3 \) the vortex reaches below the impeller due to suction and the particles are accumulated there lowering its retention.

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