Intensification of Precipitation Using Narrow Channel Reactors: Magnesium Hydroxide Precipitation

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Precipitation of magnesium hydroxide using narrow channel reactors has been studied. Effects of channel dimensions (two square cross-sectional area channels with areas 1 and 2 mm²), type of mixer (Y and cross mixer), flow rate of the reaction mixture, and reaction parameters on the particle size and particle size distribution of magnesium hydroxide have been studied. Reaction parameters studied were the effect of the concentration of magnesium chloride, temperature, pH, and addition of the cation Al³⁺. Some tests were carried out in a stirred batch reactor for comparison with the narrow channel reactors. Comparison of mean particle size of the two reactors on a power consumption basis clearly indicates the superiority of the narrow channel reactor. The results clearly show that the narrow channel reactor is a much more compact process equipment having significantly lower capital and operating costs as compared to a conventional stirred batch reactor yielding simultaneously a better product. All these advantages lead to an intensified process.

1. Introduction

In search of environmental friendly and safe fire retardants, there is increasing attention to inorganic compounds such as magnesium hydroxide.¹,² Magnesium hydroxide is used in flame retardant composite formulations because of its ability to undergo endothermic dehydration in fire conditions. Moreover, it does not evolve toxic and corrosive substances upon combustion and it can be used at higher processing temperatures than the most widely used aluminum trihydrate fillers. Magnesium hydroxide begins to decompose above 330 °C (i.e., 100 °C higher than aluminum trihydrate) to give magnesia and water vapors. In the flame phase, water vapor forms an envelope around the flame, which tends to exclude the air and dilute the flammable gases. Water vapor reacts endothermically with the flame radicals. The MgO residue becomes a conduit through which heat is conveyed away from the flame area, slowing decomposition of the polymer.³ Magnesium hydroxide also finds application in wastewater treatment, solid liquid separation, production of catalysts, etc.⁴ The key parameters in its use as a fire retardant are its particle size, agglomeration level, and particle size distribution (PSD).

Magnesium hydroxide can be obtained by a reaction between magnesium chloride and an alkali. The solubility of Mg(OH)₂ in aqueous media is extremely low (2.289 × 10⁻⁴ mol/L at 18 °C).⁵ At a very low concentration of 5 × 10⁻³ mol/L, the induction period for magnesium hydroxide precipitation is 1 s and it decreases sharply with increasing concentration.⁴ Hence, the appearance of the precipitate is instantaneous, indicating that micromixing can play an important role in deciding the PSD.

Determination of the relationship between the precipitation condition and product morphology is a major challenge. On an industrial scale it is necessary to produce large quantities of a uniform precipitate. Conventionally stirred batch reactors are used for precipitation reactions, but the scaling up of stirred batch reactors poses severe problems as the volume of the reactor increases. This results in a wide particle size distribution.

For such a complex system, the use of tubular reactors is very interesting because of the relative ease of using them to produce uniform and consistent precipitates in a continuous mode. The scaling up of such a system is rather scaling out, which can be done by just multiplying the individual number of tubular reactors. Some information is available on precipitation of calcium carbonate in narrow channel reactors.⁶,⁷ However, there is no published literature available on precipitation of magnesium hydroxide in a narrow channel reactor. The objective of this article is to investigate the effect of mixing and reaction parameters on the particle size and its distribution for precipitation of magnesium hydroxide in narrow channel reactors.

2. Narrow Channel Reactors

Stirred batch reactors suffer due to compositional homogeneity problems. On the other hand, continuous flow reactors develop parabolic velocity profiles resulting in similar disadvantages. The subdivision of the reaction mixture into a plurality of discrete volumes can result in uniform and consistent mixing conditions. These segments pass as plugs along the narrow channel reactor, and the problem of back mixing is reduced. Using this principle, Lemaitre et al.⁸ conceived a continuous tubular reactor, the segmented-flow tubular reactor, which yields a plug-flow regime. This reactor uses two immiscible phases to create individual micro-volumes of previously well-mixed reactants.

This reactor had been successfully used in the case of reactive precipitation where the mixing step is of major importance for the chemical and physical nature of the synthesized precipitate.⁸ Within each volume of
the reaction mixture conditions for the precipitation reaction were substantially identical; hence a uniform product was obtained from each volume of the reaction mixture. In this respect, it is particularly preferred that the individual volumes of the reaction mixture are of similar (ideally, equal) size and that the individual volumes of the separating fluid are also of similar size. This ensures uniform conditions in each subbatch. It is necessary that the separating fluid is inert toward the reaction mixture.

The advantages of a segmented-flow narrow channel reactor can be summarized as follows: The segmentation of the reaction mixture favors a high uniformity of the precipitation conditions. The flow in the reactor behaves as a true plug flow. In each segment the reaction mixture has exactly the same residence time and exactly the same history, and as a result, the precipitate obtained from each segment possesses highly homogeneous characteristics in terms of chemical composition, morphology, and size. In view of the above advantages, some investigators investigated a narrow channel reactor for reactive precipitation. Calcium carbonate precipitation studied in a narrow channel reactor of square cross-sectional area and without segmentation showed that the narrow channel reactor gave smaller particle sizes than a stirred batch reactor, reflecting the mixing effectiveness of reagents inside the channel. According to this study the influence of the flow rate on the particle size was not significant and smaller particles were obtained from a smaller size reactor. Vacassy et al. employed a segmented-flow tubular reactor for the precipitation of calcium carbonate and studied the effects of various mixing parameters on the morphology of the calcium carbonate precipitate. They found that the formation of calcite and vaterite phases was strongly influenced by very small changes of precipitation conditions.

There is a literature report on the use of a microchannel reactor (size < 1 mm) for obtaining nanoparticles. This includes the generation of metal nanoparticles using microchannel reactors. This study showed that the size distribution of the particles was altered by flow rates of the reactant and their concentration. If the concentration of the seeds was equal to or lower than the concentration of Au, the mean particle diameter increased with decreasing flow rate and only particle growth was dominant. Some other studies on microchannel reactors that give an idea about the mixing performance include the performance of the mixing in a micromixer and the nitration of benzene. The investigation on the performance of mixing in a micromixer showed that mixing behavior is mainly influenced by channel height and direction. Nitration of benzene carried out in a microchannel reactor revealed that reducing the internal diameter of the channel tube significantly enhanced the reaction performance. There are literature reports on gas–liquid flows in narrow channel reactors that define a microchannel reactor on the basis of surface tension forces. For gas–liquid flows channels of around 1 mm can be considered as microchannels. This channel size is smaller than that evaluated from the Laplace constant, i.e., \( \frac{\sigma}{\gamma \sqrt{(p_{\text{L}} - p_{\text{G}})}} \), where \( \sigma \) is the surface tension. The Laplace constant for the air–water system at atmospheric pressure and ambient temperature is 2.73 mm.

3. Experimental Section

3.1. Experimental Procedure. In the present work an aqueous phase homogeneous reaction between magnesium chloride salt (99% purity) and sodium hydroxide (99% purity) was employed for the precipitation of magnesium hydroxide. Aqueous solutions were prepared in distilled water.

The narrow channel reactor employed consists of two main independent parts: the mixer, where mixing and segmentation take place, and the channel, where the reaction proceeds. Two types of mixers, a Y mixer and a cross mixer, were employed to study the effect of mixing of the two reactants prior to their entry in the narrow channel. Figures 1 and 2 show Y and cross mixer reactors, respectively. The effect of the channel diameter was studied in two channels with the same square configuration but cross-sectional areas of 1 and 2 mm² (reactors A and B, respectively) with the Y mixer. These reactors were prepared by machining and bonding two acrylic sheets. The segmentation was created by using air. Peristaltic pumps supplied the two-reactant streams, one containing magnesium chloride and the other containing sodium hydroxide in stoichiometric proportion. A third peristaltic pump supplied air as the segmenting fluid. The segment length of the reaction mixture was observed, and the flow rate of air was adjusted to keep the segmented volume identical for each experiment.

The reactants were injected into a restricted volume where dissipation of kinetic energy is ensured thorough mixing. Mixing and segmentation take place simultaneously in the mixer chamber, and the product mixture is expelled as a segmented flow. The slurry flow rate for this investigation was varied in the range of 0.45–0.8 mL/s.

The conversion of magnesium chloride was determined by filtering the outlet slurry through a Whatman filter paper and drying it in an oven at 85 °C. The compositional analysis of the precipitate was done by complexometric titrations using Mordant black indicator and EDTA.

Some experiments were also carried out in a well-stirred vessel. The vessel had an internal diameter of 15 cm and a capacity of 3 L and was equipped with four standard baffles and a standard six-blade disk turbine impeller. Reactant solutions, aqueous sodium hydroxide and magnesium chloride, were added simultaneously to
the reproducibility of the analysis was within ±3%. As explained below, the particles in the aqueous product suspension can be present as agglomerates of several particles. These agglomerates are a result of high surface energy of the individual, small particles. These particles agglomerate due to physical forces in order to lower the overall free (surface) energy. To get the true intrinsic individual particle size, these agglomerates need to be broken down with a surfactant. By trial and error, Tween 20 was found to be the best surfactant for the present system comprising mainly Mg(OH)$_2$ particles.

3.2. Analysis. 3.2.1. Particle Size Analysis. The outlet slurry was analyzed in a Coulter (LS 230) particle size analyzer, which uses light scattering technique for analysis. Duplicate particle size analysis was performed for each sample, and the volume average crystal size was determined as

$$D_p = \sum n_i d_{pi}$$

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3.2.2. Scanning Electron Microscopic (SEM) Analysis. For this purpose, a Philips SEM Model 620 was used. The purpose of the SEM was to obtain the size of the agglomerates and also the number of the particles in the given agglomerate. Therefore, for this analysis no surfactant was employed.

From the above it is evident that the Coulter particle size analyzer gave the true, intrinsic size distribution, whereas the SEM provided the morphology and extent of agglomeration of individual particles.

4. Results and Discussion

4.1. Effect of Temperature. The effect of temperature on the volume average particle size (PS) is shown in Figure 3. The experiments were carried out at three temperatures, 22, 30, and 60 °C, in reactor A. The concentration of magnesium chloride was 1 mol/L, and the flow rate of the outlet slurry was 0.45 mL/s. As can be seen from Figure 3, there is no significant variation in the PS with temperature. Hernist et al. have explained the results based on the fact that the isoelectric point of magnesium chloride is 12; therefore, when the pH of the slurry is above 12 the ionic charge on the particles is negative and sodium ions are sorbed on the surface of the particle, hindering fresh incoming magnesium ions and resulting in smaller particles. These smaller particles aggregate to give an apparently larger particle size. This increase in size is mainly due to agglomeration rather than growth of discrete particles. By contrast, when the pH is less than 12, growth of particles occurs by incoming magnesium ions. This results in individual larger particles, which have less tendency to agglomerate; hence the average true particle size decreases.

4.2. Effect of pH. The effect of pH on the PS of the precipitated magnesium hydroxide is shown in Figure 4. The reactions were carried out in reactor A. It can be observed from Figure 4 that PS increases with increase in pH. The increase in particle size is not significant when pH increases from 9 to 11.5. However, the increase in PS is approximately 30% when pH increases from 11.5 to 13.

The explanation of the above results can be found from studies in stirred batch reactors. Phillips et al. investigated the effect of pH on magnesium hydroxide particles. Their SEM analysis revealed that at lower pH (pH 9.5) particles are more developed and less agglomerated than at higher pH (pH 12.5). They attributed this to higher nucleation rates at high pH than at lower pH. Hernist et al. explained the results based on the fact that the isoelectric point of magnesium chloride is 12; therefore, when the pH of the slurry is above 12 the ionic charge on the particles is negative and sodium ions are sorbed on the surface of the particle, hindering fresh incoming magnesium ions and resulting in smaller particles. These smaller particles aggregate to give an apparently larger particle size. This increase in size is mainly due to agglomeration rather than growth of discrete particles. By contrast, when the pH is less than 12, growth of particles occurs by incoming magnesium ions. This results in individual larger particles, which have less tendency to agglomerate; hence the average true particle size decreases.

4.3. Effect of Flow Rate. Figure 5 shows the effect of flow rate on the intrinsic particle size obtained from the Coulter particle size analyzer for different concentrations of magnesium chloride in reactor A. The intrinsic PS decreases sharply with flow rate for a higher concentration of magnesium chloride (1 mol/L). The decrease is approximately 51%, when the flow rate
is increased from 0.45 to 0.80 mL/s. This is due to two factors: (1) At high MgCl₂ concentrations the degree of supersaturation is high and therefore nucleation is very rapid and extensive. Such nuclei are smaller in size. (2) With an increase in flow rate, the nuclei produced in step 1 spend less time in the reactor, which curtails their growth. The overall result is thus a lower intrinsic particle size. At lower concentrations such as 0.2 mol/L, the supersaturation is much lower and thus the nucleation process does not dominate the overall particle size. It is also likely that a major part of the growth of the smaller number of nuclei formed occurs during the mixing process itself. With an increase in flow rate again these nuclei spend less time in the reactor and thus the growth in the main reactor part is less. Therefore, a marginal decrease in the intrinsic particle size is observed when the flow rate is increased from 0.45 to 0.80 mL/s.

As mentioned in section 3.2, the very small particles tend to form agglomerates. To confirm this agglomeration, SEM of two samples with magnesium chloride concentration of 1 mol/L and flow rates of 0.45 and 0.80 mL/s was performed. The micrographs of the analysis are shown in Figures 6 and 7. Figure 6a shows particles at 0.45 mL/s flow rate and Figure 6b shows a magnified single agglomerated particle at the same flow rate. Agglomerate size as large as 100 μm can be seen, which indicates the high agglomeration tendency of the particles. Figure 7 shows particles at 0.80 mL/s flow rate. In this case, the intrinsic particle size and agglomeration are much less. This is likely to be due to much more effective mixing at the higher flow rate used for the generation of particles shown in Figure 7. Further, higher flow rate implies a higher solid—liquid shear and solid—solid impacts, which may be contributing to the breakup of some agglomerates. These micrographs support the argument concerning the true and apparent (agglomerated particles) size.

Figure 8 shows the variation of intrinsic PSD for reactor A at a concentration of 1 mol/L magnesium chloride. With the increase in flow rate the PSD becomes sharper due to better mixing conditions at higher flow rates. In the case of calcium carbonate precipitation, Trippa and Jachuck⁶ and Vacassy et al.⁷ found that the flow rate effect on mean particle size of the precipitate was secondary. However, their investigation was at low supersaturation levels and no data were provided for higher supersaturation (such as for some experiments in this work) where agglomeration of the calcium carbonate can be dominant.

4.4. Effect of Channel Cross-Section Size. To study the effect of channel cross-section size, reactions were also carried out in reactor B and the results of reactor B were compared with those of reactor A. Figure 9 shows the effect of flow rate on mean particle size at two different concentrations of magnesium chloride in reactor B. It can be observed that with increasing flow rate the particle size decreases. This is the case at all
concentrations of magnesium chloride studied. At the concentration of 1 mol/L, when the flow rate increased from 0.45 to 0.80 mL/s in reactor B, the decrease in particle size was 6%, while in reactor A under similar conditions it was 51% (Figure 5). This shows the superiority of mixing in a small channel over the larger one. Figure 10 shows the PSD in reactor B at concentration of 1 mol/L. The PSD is similar for all flow rates.

Figure 8. Particle size distribution comparison for different flow rates (concentration of MgCl₂ = 1 mol/L; reactor A): ×, flow rate = 0.80 mL/s; ▲, flow rate = 0.75 mL/s; ◆, flow rate = 0.60 mL/s; ○, flow rate = 0.45 mL/s.

Figure 9. Effect of flow rate on volume average particle size at various concentrations of magnesium chloride in reactor B: ▲, concentration of MgCl₂ = 0.2 mol/L; ◆, concentration of MgCl₂ = 1 mol/L.

4.5. Effect of Concentration of Magnesium Chloride. As shown in Figures 5 and 9 for reactors A and B, respectively, with an increase in the concentration of magnesium chloride the particle size decreases. It can be derived as follows. The pressure drop in the channel can be given as

\[ \Delta P = \frac{2\rho V^2 f L}{D_h} \]

where \( f \) is the friction factor. It is well-known that in microchannel reactors laminar conditions prevail. Hence the friction factor for laminar flow in square channel can be given as\(^{15}\)

\[ f = \frac{14.2}{Re} \]

The power input is the product of pressure drop and flow rate:

\[ P = (\Delta P)Q \]

The power per unit mass of product is given by:

\[ P_m = \frac{P}{Q_{otx}} \]

where \( x \) is the mass fraction of product in the slurry and \( r \) is the residence time.

By use of the above equations, the power input per unit mass of solid produced in a narrow channel reactor is given by

\[ P_m = \frac{28.4\mu Q^2}{\rho D_h^6 x} \]  \hspace{1cm} (1)

This expression itself indicates the strong influence of channel diameter on the specific power and explains the reason for the smaller particle size obtained in reactor A.

Figure 11 shows the specific power input in two reactors per kilogram of product formed for 1 mol/L concentration of magnesium chloride at complete conversion. The increase in the specific power with increase in the flow rate for reactor B is not as steep as for reactor A, in conformity with eq 1.

The mixing effectiveness in microchannels is given in terms of the Fourier number as follows:

\[ F_0 = \frac{D_t}{\bar{\lambda}^2} \]

For complete micromixing, \( F_0 > 1 \). In narrow channel reactors, the channel width can be considered the characteristic length. Hence with an increase in channel width, \( \lambda \), the mixing effectiveness decreases.

Mixing effectiveness can also be expressed in terms of mechanical power provided for mixing. The equation is
well-known that, with increasing supersaturation, the particle size decreases. As explained earlier, at higher concentration (1 mol/L) the particle size decreases more sharply with flow rate than at lower concentration (0.1 mol/L). To confirm the lower agglomeration tendencies at lower concentration, selected samples were analyzed under SEM. Figure 12 shows micrographs of the particles at a concentration of 0.1 mol/L; flow rate = 0.45 mL/s; reactor A. (b, bottom) Micrograph of magnesium hydroxide particles with higher magnification. Concentration of MgCl₂ = 0.1 mol/L; flow rate = 0.45 mL/s; reactor A.

12b shows a magnified particle, which is formed by not more than two individual particles. Thus, the agglomeration is limited to only two particles, each of which is a distinct and well-developed particle. This is not the case for 1 mol/L concentration, where many more than two particles (each of which is of submicron size) form large agglomerates (Figure 6). Thus, when the reactant concentration is relatively high, extensive agglomeration occurs.

4.6. Effect of Type of Mixer. The effect of angle of mixing of two reactants prior to the reaction was studied with two mixer configurations: Y mixer and cross mixer. The concentration of magnesium chloride was 1 mol/L, and the flow rate was 0.45 mL/s. This effect was studied using the 1 mm² channel reactor. It was found that the particle size obtained with the Y mixer was larger (14.70 μm) than that obtained with the cross mixer (12 μm), but the PSD in the Y mixer was sharper than that in the cross mixer. Hence it can be concluded that the mixing angle of reactants prior to the reaction has a definite effect on the quality of the magnesium hydroxide precipitate. The reason for small particle size in the cross mixer is that it allows rapid mixing through direct impingement of the reactants, which gives smaller particles. Vacassy et al.⁷ also obtained a wider distribution with the cross mixer for precipitation of calcium carbonate. Further, they found that conditions in the cross mixer lead to vaterite spherical particles and that the formation of the calcite phase of the calcium carbonate precipitate is suppressed.

4.7. Conversion. It was found that very high conversions (>95%) could be obtained for all flow rates employed in both narrow channel reactors. The highest conversion was 99% with a flow rate of 0.75 mL/s in reactor A. This may be attributed to better mixing in reactor A due to small channel cross-sectional area and high flow rate. This is very interesting for industrial practice because higher conversions can be achieved even at low residence time. Effectively the reactor size for a given rate of production is much lower for narrow channel reactors, implying process intensification through their use.

4.8. Comparison of Narrow Channel and Stirred Batch Reactor. For the comparison with narrow channel reactors, some experiments were carried out in a stirred batch reactor under otherwise similar conditions. Figure 13 shows the variation of volume average particle size with power consumption per unit mass of
product in narrow channel and stirred batch reactors. It can be observed that with increasing power the input particle size decreases in the stirred batch reactor. As the stirring rate increases, the power dissipated increases and hence smaller particles are obtained. The smallest particle size obtained in the stirred batch reactor was 12.2 µm. The power consumed per unit mass of the solid product in the stirred reactor can be calculated from the power number. The relation used for the calculation is

$$ P_m = \frac{N_p n^2 D_s^5 \rho}{M_s} $$  \hspace{1cm} (2) 

$N_p$ for a disk turbine is 5.5 as a turbulent zone was assured for the operating conditions.

For a narrow channel reactor the power consumed per unit mass of product was calculated from eq 1.

From Figure 13, it can be observed that the specific power requirement in the narrow channel reactor is very low as compared to the stirred batch reactor. For the range of concentration covered in this work, the narrow channel reactor always gives smaller particles than the stirred batch reactor. This is an important advantage of the narrow channel reactors in industrial practice. Table 1 gives a comparison of the reactor volumes for narrow channel and stirred batch reactors under otherwise similar conditions. It is obvious from Table 1 and Figure 13 that the narrow channel reactor affords an intensified process in terms both of capital and operating costs.

There is a sharp decrease in PS with increasing $P_m$ for the narrow channel reactor, whereas for the stirred batch reactor a 4-fold increase in $P_m$ is required to decrease the PS by half from 22 to 12 mm. This clearly indicates the highly effective utilization of the power input in the narrow channel reactor.

4.9. Effect of Time and Length Scales on Growth Rate. The effect of the time scale on growth can be studied by assuming that the chemical reaction and nucleation take place spontaneously. Figure 14 shows the effect of residence time and channel width on the particle size at a MgCl$_2$ concentration of 1 mol/L. From Figure 14, it is clear that with increasing residence time the particle size increases. Further, it may be noted that in the lower range of residence time ($<1$ s) the increase in the particle size is appreciable. However, a plateau value is reached for residence time above 1 s. Visual tests carried out showed that the mixing time in the studied reactor was $<1$ s, which is also supported by the results of Trippa and Jachuck. For the stirred tank reactor used, the mixing time is 5 times the circulation time, which is greater than 3 s in most of the cases. It is evident that the data for the two reactors fall on a smooth curve.

4.10. Morphology of Magnesium Hydroxide Particles. There are many studies available on the morphological behavior of magnesium hydroxide, which consist of SEM or other photographic analysis. The studies were carried out at very low concentrations of the reactants ($\sim 1.2 \times 10^{-3}$ mol/L) and in either a stirred batch or an MSMPR reactor. Even at such low concentrations, the images obtained in the above studies reveal that there are several agglomerated particles with a variety of morphological structures. In the case of narrow channel reactors employed in the present work, when the concentration was 0.1 mol/L well-defined spherical crystals with very little agglomeration were obtained. This is evident from Figure 12. This is more evidence of the superiority of narrow channel reactors over stirred batch reactors.

It is also important to note that, in the narrow channel reactors with changing mixing conditions and concentration of reactants, the particle morphology changes. At lower flow rate a single particle in the agglomerated bunch of particles at a concentration of 1 mol/L (Figure 6b) is triangular shaped. When the flow rate is high, the particles are rectangular in shape. At lower concentration but at the same flow rate the particles are spherical; i.e., growth occurs from all sides (Figure 12).

5. Conclusions

Precipitation of magnesium hydroxide in narrow channel reactors shows better results in terms of lower particle size, sharper particle size distribution, and lower power consumption than the conventional stirred batch reactor. Mixing parameters have a significant effect on the PSD of magnesium hydroxide. It was found that a smaller cross sectional area channel gives smaller particle sizes. The mixer angle for mixing of reactants prior to the reaction is also an important factor. It was found that agglomeration is dominant at high concentration. More well-defined particle morphologies were obtained at lower concentrations. Comparison of the performance of the narrow channel reactor and the stirred batch reactor clearly indicates that the use of the former results in an intensified process.

Nomenclature

- $D$ = diffusivity (m$^2$/s)
- $D_s$ = impeller diameter (m)

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Power (kW)</th>
<th>Reactor Vol (m$^3$)</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirred Batch</td>
<td>5685</td>
<td>28.7 (3$^4$)</td>
<td>24</td>
</tr>
<tr>
<td>Narrow Channel (1 mm$^2$)</td>
<td>1565</td>
<td>0.205 $\times$ 10$^{-6}$ (415$^5$)</td>
<td>24</td>
</tr>
</tbody>
</table>

$^a$ Concentration of MgCl$_2$ = 1 mol/L. $^b$ Number of batches. $^c$ Number of narrow channels.

**Table 1. Comparison of Narrow Channel and Stirred Batch Reactors for Production of 5000 kg of Magnesium Hydroxide**

![Figure 14](image-url)
\( D_h \) = hydraulic diameter (m)  
\( D_p \) = average particle diameter (\( \mu \)m)  
\( d_{pi} \) = diameter of particle \( i \)th channel (\( \mu \)m)  
\( f \) = friction factor  
\( L \) = length of channel (m)  
\( n \) = speed of stirring (rev/s)  
\( N_p \) = power number  
\( P \) = power (W)  
\( P_m \) = power per unit mass of product (W/kg)  
\( \Delta P \) = pressure drop (N/m²)  
\( Q \) = flow rate of the outlet slurry (mL/s)  
\( v_i \) = volume fraction in \( i \)th channel  
\( x \) = fraction of product in outlet slurry (kg/kg)  
\( \lambda \) = characteristic mixing length (m)  
\( \rho \) = density (kg/m³)  
\( \tau \) = residence time (s)  
\( \mu \) = viscosity (kg/m s)  

**Literature Cited**


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