Infinity Turbine: SDR Technology Review for Nanoparticle Production

By Eric Gerber (under contract by Infinity)

November 6, 2017

Executive Summary

This report ended up taking a different turn than originally planned, but contains valuable information on the known ability of using SDRs for nanoparticle production. The report covers articles and reviews detailing using an SDR to make nanoparticles, market research of nanoparticles of interest, and makes a business case/pitch for using your SDR to make nanoparticles. Overall the goals of the report are to give a detailed description of what is known to work using an SDR to make nanoparticles, help someone looking to make novel nanoparticles, like quantum dots, using a SDR make informed decisions on operating parameters, and detail markets available for the SDRs.

In a broad sense, SDRs are a very new type of processing unit that has had new applications discovered every year. All the articles used in this report are under 10 years old, with the newest one being published this year. This demonstrates how new SDRs are, especially in this field. While there is no publicly available information on using SDRs to make quantum dots, I believe that it is possible and most likely is being optimized currently in the private market.

With the research I have conducted and summarized, someone looking to use your SDR to make quantum dots or other novel nanoparticles not detailed here would be able to make informed decisions on operating parameters such as reactant concentrations, disc speeds/ characteristics, flow rates, etc.

And finally, using this report, one could easily make a business case to use your SDR to start making silver nanoparticles which have a large current market. Titanium dioxide and pharmaceuticals are another good option to pursue, albeit should be entered with caution. While the processes are possible with an SDR, the cost and production ability are less defined and thus might not be economically feasible.

Altogether, most of the markets discussed here are rapidly growing and are going to have new players entering consistently. With the right advertisement and focus, this could drive demand for your reactors. I would recommend focusing not explicitly on quantum dots, but on nanoparticles altogether. I'd also include specifics, like being able to make silver nanoparticles with a high production rate using a green process. Also, include all the possible nanoparticles I have listed here and keep a research search notification for new papers and patents on other nanoparticles made with an SDR to add. You never know which material is going to have the next great use. I'd also suggest if you have the R&D budget, looking into making silicon or cadmium nanoparticles with your SDR. Like you mentioned, having explicit proof that it works with your product would be a very great pitch. Although I'd be hesitant to release that information publicly if you're able to do so. If you can make them continuously and cheaply you might want to look into getting a patent yourself on the process.

1. Introduction

Before getting into the the production of nanoparticles via SDRs, it is worth looking into the basic design of an SDR, how they are used to make nanoparticles, and an overview of what a nanoparticle even is and how it is useful.

1.1 Background on SDR

A big field of interest as of lately has been process intensification which is a design approach that focuses on smaller, cleaner, safer, and more energy efficient processes [1]. One design that has received considerable attention as of late has been the spinning disc reactor (SDR). As seen in Figure 1, its basic design includes one or more liquid streams being flowed onto a quickly rotating disc.

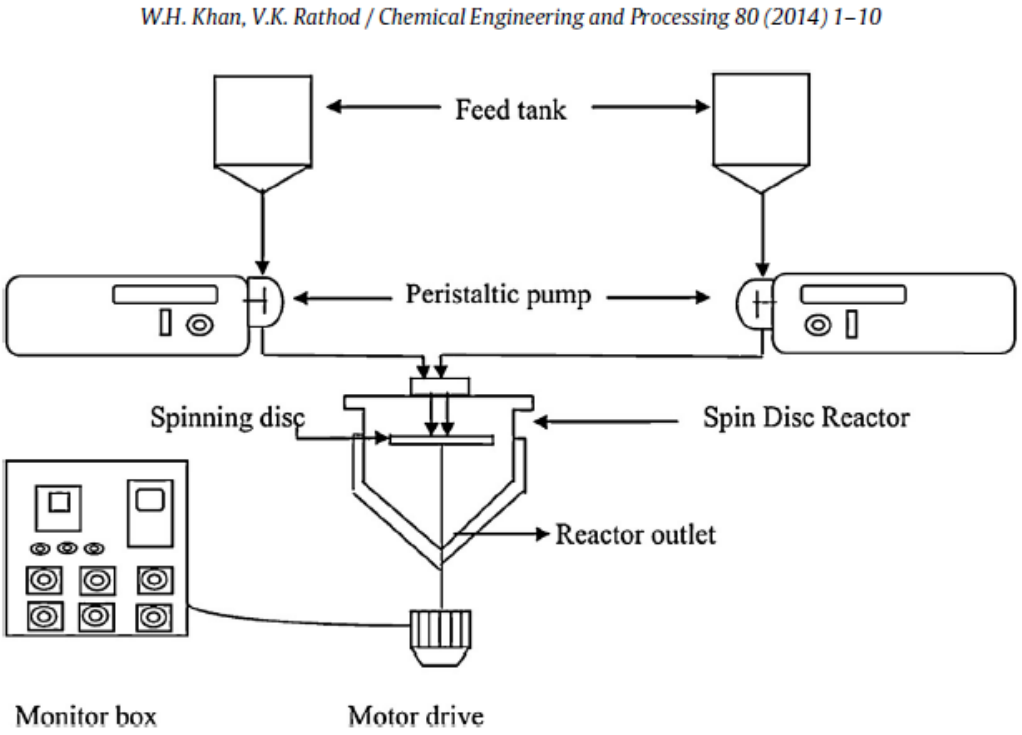


Figure 1. Basic design of a spinning disc reactor [2].

The centrifugal acceleration from the rotation creates a very thin liquid film which significantly heightens the mass transfer and micro-mixing ability of the liquid streams [3]. It also allows for more process control due to additional variables in the process including RPMs of the disc, the texture on the disc, the disc temperature, the injection site along the disc, disc size, pressure in

the reactor, and environment in the reactor (can include speciality gas injection into reactor space). It also is a continuous feed reactor which can be applied to many processes that have relied on large volume and high residence time designs like batch or continuously stirred tank reactors (CSTR).

1.2 Background on Synthesis Methods

While the SDR can be used for many different processes, it excels greatly in a specific few. These include processes that rely on precipitation and uniformly mixed reactants. These traits allow for SDRs to be used in the “bottom-up” production of nanoparticles, where particles are created through nucleations and subsequently crystal growth. This is where batch reactors and CSTRs aren’t as easily applied due to their high volumes and lack of sufficient mixing ability. “Top-down” processing where bulk material is ground down into nanoparticles is typically avoided when trying to achieve nanoparticles of a certain size and narrow size distribution due to the lack of control over the process [4].

One process in this category is reactive precipitation. This reaction is the combination of two or more reactants to produce a product which precipitates from the medium. When using SDRs for reactive precipitation, they have been shown to be able to make smaller particles with a more narrow range in particle size distribution [3]. This has been shown for the production of nanoparticles for quite a few compounds including barium sulfate, copper oxide, magnesium hydroxide, silver, silver iodide, titanium dioxide, and more [5] [6] [7] [8] [9] [3] [10]. The production of nanoparticles from this “bottom-up” reaction requires a high level of control of the nucleation and growth processes. Both of these processes are controlled by the supersaturation of the medium. A SDR allows for control of the micro-mixing of the liquids and thus indirect control of the distribution of supersaturation through the vigorous hydrodynamic conditions generated at high disc and flow rates [3].

The other main process in this category is solvent-nonsolvent precipitation. This reaction starts with the product dissolved in a solvent near saturation. Then a non-solvent is added in through drop-wise addition through supersaturation until the product starts to precipitate out of solution. An example of this would be the addition of an aqueous solution onto an organic stream with a hydrophobic solute in dissolution [2]. Again this process benefits from the micro-mixing ability of SDRs.

A final thing to highlight in this section is that in these types of reactions, a protecting agent is often employed to avoid agglomeration of the nanoparticles after synthesis. These agents have multiple charges that stabilize the nanoparticles and help them avoid agglomeration. They play no part in the actual reaction occurring.

1.3 Background on Nanoparticles

But why even focus on nanoparticles? Nanoparticles are defined by the ASTM to be particles with two or three of their dimensions to be between 1nm - 100nm [11]. In this range particles have interesting properties due to the quantization of energy levels and large surface area to volume ratios.

One thing of these properties is that nanoparticles often have tunable optical and electrical properties. When controlling for size and shape, it is possible to control the solar absorption of the particle. In general absorption of solar radiation is higher as well for nanoparticles [12]. When nanoparticles are small enough and made of a semiconducting material, they can be considered “quantum-dots” due to their quantization of electronic energy levels. These particles are being investigated more with applications includes transistors, solar cells, LEDS, medical imaging, and drug delivery [14].

Nanoparticles can also be produced to be core-shell particles, allows for the crafting of certain particles with dual properties. An example of this is magnetic TiO2 particles, where the core of the particles is Fe3O4, which is subsequently coated with TiO2. This allows for the particles to be magnetic, while retaining the optical properties of TiO2 [15].

An additional interesting effect on the nanoscale is the ability to dissolve nanoparticles of a usually non-soluble material in a solvent. This is due to the interactions between the particle surface and the solvent are strong enough to overcome density differences that would normally result in the material sinking or floating [16]. This property becomes incredibly important in the production of composite materials. A nanoparticle suspension can easily be mixed into or spin-coated or inkjeted onto another material. This would allow for a much less expensive process of producing semi-conductors with good optical and electronic properties.

Finally, the reactivity of of nanoparticles is often increased compared to bulk particles of the same material [17]. This is because reactions involving materials happens on the surface of particles, thus a high surface area to volume ratio increases the reactions site available in smaller particles.

2. Research

With some background into SDRs, nanoparticles, and how they are made, we can look into the current scene of combining the three topics. I focused my searching into verifiable synthesis methods using SDRs to produce nanoparticles via academic studies. After learning of the application of each nanomaterial, I looked into the market size and pricing of particles that I believe have established uses. Finally, I took this info and then focused the rest of the report on nanoparticles of interest which include silver, titanium dioxide, pharmaceuticals, and quantum dots.

2.1 Proof of Concept of Production

The goal of investigating academic articles was to get a general idea of the advantages and limitations of using a SDR to produce nanoparticles. While academic articles don't always translate well into commercial processes, they provide some insight into the technology and how versatile it can be.

2.1.1 Quantum Dots

This report originally was to focus on making quantum dots with an SDR, but after initial research I found that there was no publicly available research into making quantum dots with an SDR. I believe after reading all the info that I have, that SDRs could be used to make quantum dots, but that either it is not profitable or is kept a trade secret. As seen later in **Section 2.2.5**, the market for quantum dots has exploded over the last 5 years and is expected to continue to explode. Because of this, I decided to compile all the research I conducted on what has been shown to work for SDRs in the production of different interesting nanoparticles. This makes up the rest of this proof of concept section. As mentioned before, quantum dots are small nanoparticles made out of semiconductor material. The info discussed in this section should allow someone to make informed decisions when attempting to make quantum dots of interest using an SDR.

The two processes that I believe are worthwhile looking into using an SDR to make quantum dots are the two discussed in **Section 1.2**. The first is using reactive precipitation and the other would be using the solvent/non-solvent precipitation as described before.

Reactive precipitation would require some thinking on which reactions to pursue and which solvents to use to allow for the precipitation. However, a lot of the materials are made using CSTRs now via reactive precipitation so you may be able to mirror those processes just in an SDR [18]. Most quantum dots are made of a cadmium based material and I would imagine reacting a cadmium based solute with the other compound bonded (selenide, telluride, sulphide) and the right solvent to make it insoluble after the reaction "should" work. Silicon and indium arsenide have joined the market recently since cadmium is considered toxic and expensive, and thus the same should be pursued for indium arsenide. Silicon would be different, but a reduction of silica or silicon halides seems reasonably possible.

The solvent/non-solvent process would be interesting to investigate. I can't make an educated guess on if any would work because this type of process is much more dominated by the thermodynamics of nucleation and crystal growth, but the bulk material dissolved in a solvent should allow for precipitation with the addition of a non-solvent. The size would be more predetermined, but there's a chance it works out how one would want without agglomeration with the right protecting agent.

2.1.2 Silver

The first study looked into a green process of synthesizing silver nanoparticles using a spinning disc reactor. Figure 2 details the experimental setup of the process. It involves a semi-batch recycle process where a silver nitrate and starch solution (Tank A) is reduced with excess glucose and sodium hydroxide (Tank B) on a vertical spinning disc and the product is returned to Tank A. After the reduction agent is exhausted, Tank A is recycled for another 5 minutes. This process ensures the reaction only occurs on the disc and avoids particle growth in the tank [8]. The starch acted as a protecting agent in this reaction to reduce agglomeration after the reaction occurs.

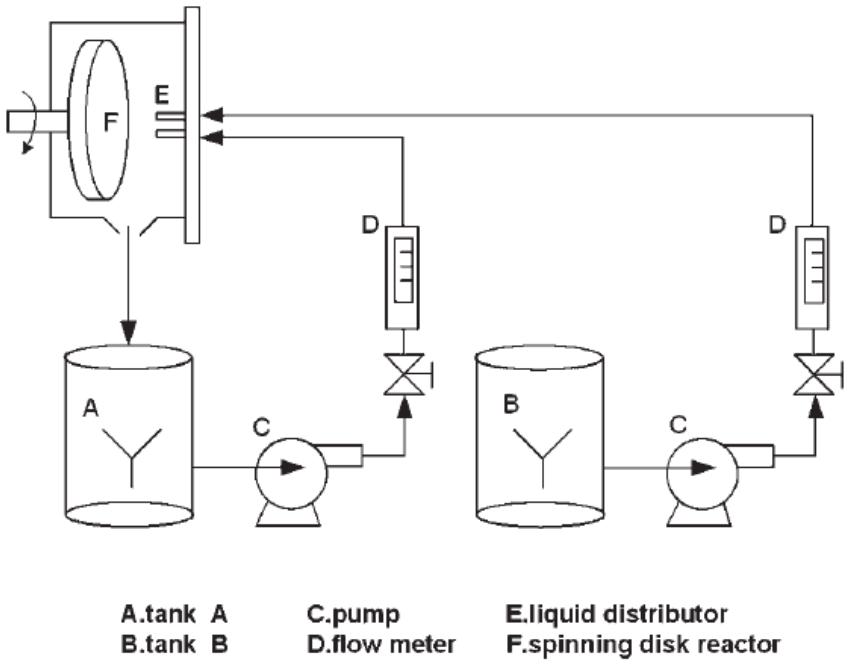


Figure 2. An illustration of the experimental setup for the production of silver nanoparticles [8].

Table 1 and Table 2 go through the specifications of the fixed and variable properties of the process.

Fixed Property	Specifications	Notes
Disc Size	19.5 cm	N/A
Ratio of Reactant Flow Rates	1:4	Solution A : Solution B
Separation of Feed Lines	5 mm	Centered on disc
Distance from Disc to Feed Lines	5 mm	N/A
Disc Orientation	Vertical	N/A

Table 1. Fixed properties in the experimental setup of the production of silver nanoparticles [8].

Variable Property	Range	Optimal Setting
Disc Speed	1000 - 4000 RPMs	1000+ RPMs
Flow Rates (Solution A)	0.8 L/min - 2.4 L/min	1 L/min
Solution A Concentrations (AgNO3/Starch)	0.01 M - 0.07 M AgNO3 0.5:1 - 1.5:1 wt ratios	0.01 M AgNO3 1:1 wt ratio
Solution B Concentrations (Glucose/NaOH)	0.01 M - 0.05 M Glucose 0.07 M NaOH	0.01 M Glucose 0.07 M NaOH

Table 2. Variable properties in the experimental setup of the production of silver nanoparticles [8].

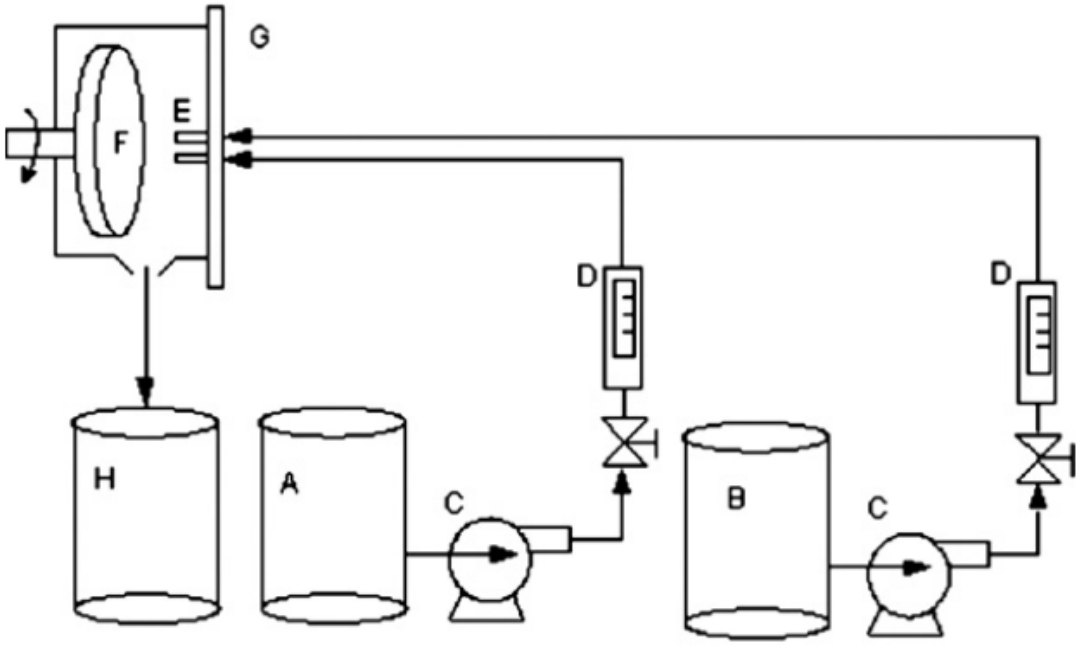
With these properties, the publishers were able produce silver nanoparticles at a yield as high as 70% and when separated and redispersed in water had a number mean average size of 5.1 nm and volume mean size of 6.9 nm, indicating a rather lower particle size distribution. They also were stable in solution for over 40 days [8]. A quick estimate of the production capacity with this process using the optimal conditions is around 33 kg/day of silver nanoparticles [9]. The main drawback of this process was the retention of the starch on the surface of the particles (2.7%w) after cleaning them. This means that they would require additional processing to remove these impurities if the goal was to use them in high purity applications like medical applications [8].

The disc speed was relatively unimportant in dictating size or yield as long as sufficient mixing occurred. When low RPMs were combined with higher starch concentrations, agglomerates formed due to the increased viscosity of the solution and lower mixing ability. The nanoparticles could be made larger by raising the glucose concentration or by raising the flow rates (while maintaining the 1:4 ratio of Solution A to Solution B). Raising the concentration of AgNO3 resulted in agglomerates starting to form [8].

Silver nanoparticles have a variety of applications, but their main ones are in inkjet formulations and as an antibacterial agent. When used as pigments in inkjet formulations they improve image quality and print reliability. When used as an antibacterial agent they have high antibacterial activity while also having no intolerable cytotoxic effects in humans [8].

2.1.3 Silver Iodide

The next study was by the same authors and looked into a process of synthesizing silver iodide particles using a SDR. Figure 3 illustrates the experimental setup. It involved a continuous reaction of a silver nitrate and polyvinylpyrrolidone (PVP; protecting agent) solution with a potassium iodide solution on a vertical spinning disc [9].



A. Storage tank for the aqueous solution of $AgNO_3$ and protecting agent
B. Storage tank for the aqueous solution of KI
C. Pump D. Flow meter E. Feeding tube F. Spinning disk
G. Spinning disk reactor H. Slurry Collector

Figure 3. An illustration of the experimental setup for the production of silver iodide nanoparticles [9].

Table 3 and Table 4 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	Specifications	Notes
Disc Size	19.5 cm	N/A
Ratio of Reactant Flow Rates	1:1	Solution A : Solution B
Separation of Feed Lines	5 mm	Centered on disc
Distance from Disc to Feed Lines	5 mm	N/A
Disc Orientation	Vertical	N/A
Flow Rates (Solution A)	0.5 L/min	N/A
Ratio of Reactant Concentrations	1:1	Solution A : Solution B

Table 3. Fixed properties in the experimental setup of the production of silver iodide nanoparticles [9].

Variable Property	Range	Optimal Settings
Disc Speed	500 - 4000 RPMs	1000+ RPMs
Solution A Concentrations (AgNO3/PVP)	0.05 M - 0.20 M AgNO3 0 g/L – 10 g/L PVP	0.20 M AgNO3 10 g/L PVP

Table 4. Variable properties in the experimental setup of the production of silver iodide nanoparticles [9].

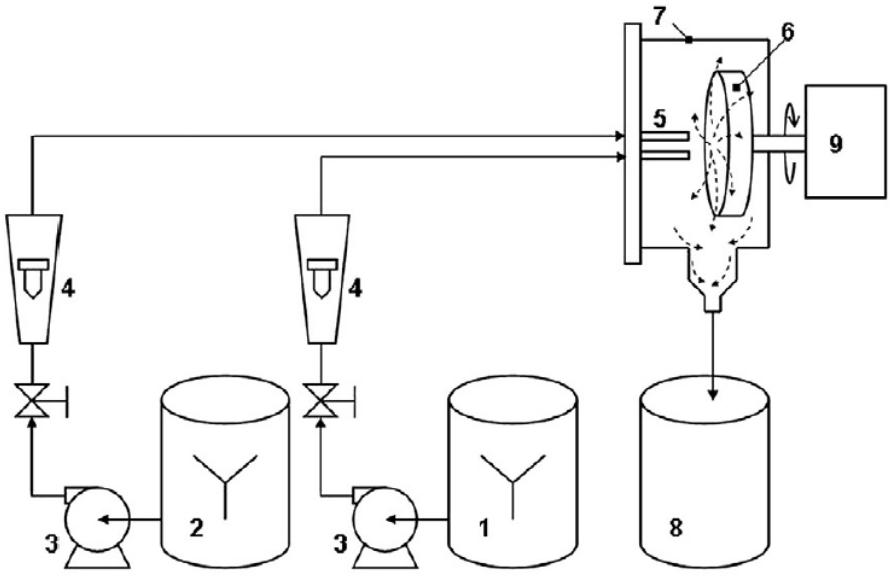
With these reaction conditions, the publishers were able to produce 23.3 kg/day of silver iodide nanoparticles with a volume mean size of 66.3 nm and an overall yield of 69% [9]. As with the silver nanoparticles, a small portion of the protecting agent (PVP in this case) is retained on the surface of these particles (3.8%wt at 5 g/L PVP and 7.9%wt at 10 g/L). Of main interest, the particles produced are partly β-phase and γ-phase particles. When the particles are of α-phase, they become superionic. This means they can act like a solid-state electrolyte, allowing for the easy movement of charge through them. Silver iodide particles can be transitioned to their α-phase through simple heating, but return to their β/γ-phase at a lower temperature. Micron sized silver iodide particles (currently the more easily made silver iodide particles), change to the α-phase at 151 C and back to the β/γ-phase at 140 C. Due to the smaller size and higher retention of PVP, the 66.3 nm and 7.9%wt PVP particles transitioned to the α-phase at 168.4 C and back to the β/γ-phase at 50 C. If this return to β/γ-phase can be reduced to room temperature, the α-phase with it's superionic properties can be retained entirely [9].

The disc speed again seemed to be insignificant in the process. At disc speeds above 500 rpms, no differences were seen in the produced nanoparticles. A higher disc speed was arbitrarily chosen to ensure mixing. Raising the PVP concentration was able to reduce particle size and decrease agglomeration (to practically nothing after 5 g/L) [9]

Silver iodide particles don't have a lot of uses in commercial applications unless they are in the α-phase. In this phase they can be used in solid-state sensors and batteries as the stand-in electrolyte. They can also be used as the internal electrode for multi-layer capacitors. For use in these applications, the transition temperature would need to be slightly lower, but it seems possible for to reach that critical point with more process optimization [9].

2.1.4 Copper Oxide

This next paper discussed the production of copper oxide nanoparticles for use in water to increase it's conductivity and thus usefulness as a heat transfer fluid. It involved the continuous reaction of copper sulfate pentahydrate ($CuSO4*5H2O$) with sodium carbonate ($Na2CO3$) using



a vertical SDR as seen in Figure 4. The resulting compound was put through a calcination process to form the resulting copper oxide (CuO) [6].

Figure 4. Experimental setup for the production of copper oxide nanoparticles [6].

Table 5 and Table 6 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	Specifications	Notes
Disc Size	20 cm	N/A
Ratio of Reactant Flow Rates	1:1	Solution A : Solution B
Disc Orientation	Vertical	N/A
Ratio of Reactant Concentrations	1:1	Solution A : Solution B

Table 5. Fixed properties in the experimental setup of the production of copper oxide nanoparticles [6].

Variable Property	Range	Optimal Setting
Disc Speed	500 - 4000 RPMs	1000+ RPMs
Solution A Concentrations ($CuSO_4*5H_2O$)	0.01 M - 0.40 M ($CuSO_4*5H_2O$)	0.10 M ($CuSO_4*5H_2O$)
Flow Rate (Solution A)	0.20 L/min - 5.0 L/min	1.5 L/min

Table 6. Variable properties in the experimental setup of the production of copper oxide nanoparticles [6].

With these experimental conditions the publishers were able to create CuO nanoparticles between 20-30 nm in size at a rate of 16.9 kg/day with a 95%+ yield. The nanoparticles could still be made at a size of less than 65 nm at double the flow rate (3 L/min) which would double the production of the nanoparticles [6].

The rotation of the spinning disc had a marginal impact on the particle size, with a smaller particle being produced from the precursor made at higher RPMs. The more impactful control on the nanoparticle size came from the reactant concentrations, with a larger size gained from higher concentrations. For example, when changing the concentration of copper sulfate pentahydrate from 0.01 M to 0.40 M, the particle size changed from 44 nm to 93 nm [6].

These particles were then dispersed in water to make it a nanofluid (fluid containing nanoparticles) to increase the conductivity of the water. The weight ratio of the dispersant (NaHMP) to CuO was between 0.78 and 3.12 (with the lower ratio at the higher solid contents). At 0.40%wt CuO (the highest solid contents tested), the conductivity of the water increased by 10.8%. While academically significant, it's hard to see this process being commercially viable [6].

2.1.5 Curcumin

Curcumin nanoparticles were produced next through a solvent/non-solvent precipitation with a SDR. Figure 1 shows the experimental setup used. It involved the addition of PVP in deionized water (non-solvent) to a solution of curcumin in ethanol (solvent) [2].

Table 7 and Table 8 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	**Specifications**	**Notes**
Temperature	30 C	N/A
Disc Orientation	Horizontal	N/A
Feed Lines Orientation	Centered on Disc	N/A
Distance from Disc to Feed Lines	1 mm	N/A

Table 7. Fixed properties in the experimental setup of the production of curcumin nanoparticles [2].

Variable Property	**Range**	**Optimal Setting**
Disc Speed	500 - 3000 RPMs	1500 RPMs
Solution A Concentration (Curcumin in Ethanol)	0.1 g/L - 1.5 g/L (Curcumin)	0.5 g/L (Curcumin)
Solution B Concentration (PVP in Water)	0 g/L - 3 g/L (PVP)	1 g/L
Flow Rate Ratios	1:1 - 1:6 (A : B)	1:4 (A:B)
Flow Rate (Solution A)	0.15 L/min - 0.45 L/min	0.22 L/min
Disc Characteristics	Smooth / Grooved	Grooved
Disc Size	15 cm / 18 cm	18 cm

Table 8. Variable properties in the experimental setup of the production of curcumin nanoparticles [2].

Curcumin particles with a size up to 220 nm and narrow particle size distribution were produced with these settings. When a narrow particle distribution wasn't need, particles from 130 nm average size to 550 nm were able to be produced. The most interesting quality of these nanoparticles was that they had a very high solubility in water compared to bulk curcumin [2].

In general, particle size decreased with an increasing disc speed. This factor topped off after 1500 RPMs. Lower concentrations of curcumin also produced smaller and more uniform particles. Past 1 g/L, the PVP concentration did not significantly impact particle size. Increasing

the water flow rate caused a decrease in particle size. Increasing the overall flow rate decreased uniformity and particle size. The disc characteristics surprisingly impacted particle size, with the grooved and larger disc producing smaller nanoparticle [2].

Curcumin is a compound found in the plant *Curcuma Longa* which has a wide variety of therapeutic applications including being used as an anticancer, anti-inflammator, antioxidant, antiulcer, immunomodulator, neuroprotector, and being used in wound healing. It's main limitations come from it's lack of solubility in water and thus bioavailability. The nanoparticles produced in this study had a much higher solubility and thus could possibly be used as a therapeutic agent effectively [2].

2.1.6 Zero Valent Iron

Zero valent iron nanoparticles (nZVI) were produced in the next article with both a batch stirred reactor (BSTR) and SDR. The experimental setup of the SDR is seen in Figure 5. The resulting particles were compared in the removal of nitrates in wastewater. The reaction is between dilute solutions of iron sulfate septahydrate (FeSO4*7H2O) and sodium borohydride (NaBH4) [19].

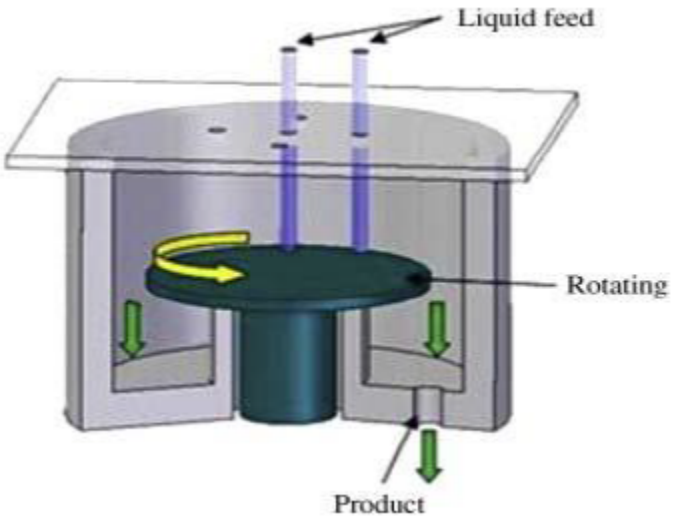


Figure 5. Experimental setup for the production of nZVI particles [19].

Table 9 and Table 10 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	Specifications	Notes
Temperature	30 C	N/A
Disc Orientation	Horizontal	N/A
Feed Lines Separation	4 cm	Centered on Disc
Disc Speed	1400 RPMs	N/A
Disc Size	8.5 cm	N/A
Solution A Concentration ($FeSO_4*7H_2O$)	0.040 M ($FeSO_4*7H_2O$)	N/A
Solution B Concentration ($NaBH_4$)	0.08 M ($NaBH_4$)	N/A

Table 9. Fixed properties in the experimental setup of the production of nZVI nanoparticles [19].

Variable Property	Range	Optimal Setting
Flow Rate (Solution A)	0.15 L/min - 0.20 L/min	0.15 L/min
Flow Rate (Solution B)	0.025 L/min - 0.05 L/min	0.0375 L/min
Height of Feed Line	2 cm - 4 cm	2 cm

Table 10. Variable properties in the experimental setup of the production of nZVI nanoparticles [19].

The nanoparticles produced had a mean diameter of 65 nm and could be produced at a rate of 0.45 kg/day. The particle distribution was very narrow in comparison to the BSTR nanoparticles. The BSTR particle's size were bimodal, pointing to the fact that agglomerates started to form. When the SDR particles were compared to the BSTR particles in the removal of nitrates, they had about 20% more removal of the nitrates. This is attributed to the higher surface area [19].

Larger particles could be made with the SDR by raising the flow rate of the iron sulfate solution (ranging from 70 nm at 0.15 L/min to 94 nm at 0.20 L/min). The changing of the sodium borohydride solution didn't impact the size of the particles as much. When the height from the disc reached 4 cm, a large spike in size occurred (68 nm at 3 cm and 80 nm at 4 cm) attributed to more splashing from the feed streams [19].
Another interesting application not investigating by this paper is the fact that iron nanoparticles are magnetic which means they can be more easily removed or manipulated when used in water treatment or other applications [20]. These particles made here could then be coated with metals or surfaces to give them functionalization while retaining their ability to be grabbed by magnets. This was shown by a paper that I will briefly mention later.

2.1.7 Magnesium Hydroxide and Magnesium Oxide

This next study investigated producing magnesium hydroxide nanoparticles [Mg(OH)2] using a SDR, and then forming MgO nanoparticles from these particles with a calcination process. The experimental setup for the Mg(OH)2 nanoparticles can be seen in Figure 6. It involved a reduction of an aqueous solution of magnesium chloride sextahydrate (MgCl2*6H2O) with an aqueous solution of sodium hydroxide (NaOH) [7].

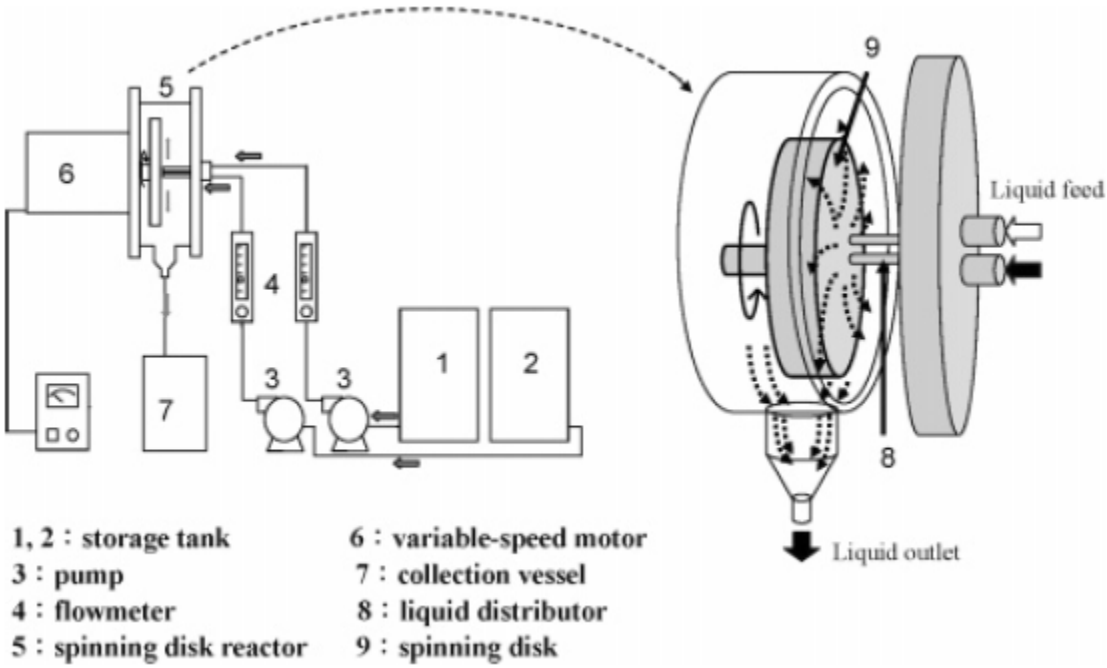


Figure 6. Experimental setup for the production of Mg(OH)2 nanoparticles [7].

Table 11 and Table 12 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	**Specifications**	**Notes**
Distance from Feed Line to Disc	5 mm	N/A
Disc Orientation	Vertical	N/A
Feed Lines Separation	7 mm	Centered on Disc
Disc Size	12 cm	Diameter
Solution A Concentration (MgCl2*6H2O)	0.20 M - 0.92 M (MgCl2)	N/A
Ratio of Flow Rates	1:1 (A:B)	N/A

Table 11. Fixed properties in the experimental setup of the production of Mg(OH)2 nanoparticles [7].

Variable Property	Range	Optimal Setting
Reactant Flow Rates	0.28 L/min - 0.75 L/min	0.28 L/min
Feed Molar Ratio	1:1 - 1:4 (A:B)	1:2 (A:B)
Solution A Concentration (MgCl2*6H2O)	0.20 M - 0.92 M (MgCl2*6H2O)	0.92 M (MgCl2*6H2O)
Disc Speed	400 RPMs - 2000 RPMs	2000 RPMs

Table 12. Variable properties in the experimental setup of the production of Mg(OH)2 nanoparticles [7].

The Mg(OH)2 nanoparticles produced under these experimental conditions had a mean diameter of 47.5 nm at a rate of ~20 kg/day (unknown yield but suggested that it was high 90% +). The nanoparticles made resembled short cylinders (like platelets). The resulting powder had 98% of the particles be smaller than 100 nm in diameter, pointing to low agglomeration. After calcination, the MgO particles agglomerated more, producing individual particles between 30 nm and 70 nm, but having a volume mean size of 150 nm [7].

The flow rate was a big factor in the size of the particles. When ranging from 0.28 L/min to 0.75 L/min, the number mean diameter changed from 47.5 nm to 143.6 nm. The molar ratio was not useful in controlling the structures due to agglomeration on the micron size with excess NaOH and low yield with excess magnesium. The solution concentrations and disc speed proved to have small controls, but not near the magnitude of the flow rate change [7].

Mg(OH)2 has been used in the past as a flame retardant when used as a composite in building material due to its ability to dehydrate. When dehydrated in the study, the nanoparticles proved to be useful in this applications. It can also be used to neutralize acid waste streams, treat flue gas, and be turned into MgO. MgO can also be used composite material, increasing the strength of the material it is used in. Due to the high production rate and seemingly good flame retardant properties, the Mg(OH)2 nanoparticles proved to be promising for commercialization [7].

2.1.8 Titanium Dioxide

Another process of interest is the production of titanium dioxide (TiO2) nanoparticles with a SDR. It follows the experimental setup shown in Figure 7. The reaction is the “sol-gel” process. This involves the hydrolysis of tetra isopropoxide (TTIP) and then the poly-condensation of the resulting titanium tetrahydroxide [Ti(OH)4] to form TiO2 nanoparticles. They also compared the nanoparticles made by the SDR to those made by a STR [3].

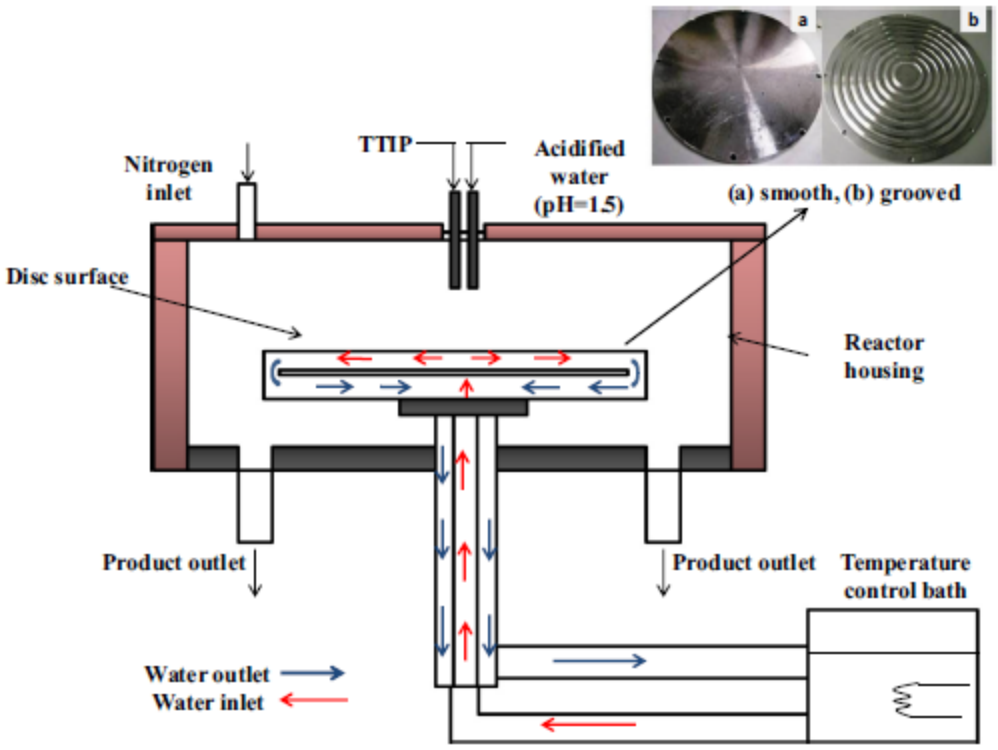


Figure 7. Experimental setup for the production of TiO2 nanoparticles [3].

Table 13 and Table 14 go through the specifications of the fixed and variable properties of the experiment.

Fixed Property	Specifications	Notes
Distance from Feed Line to Disc	5 mm	N/A
Disc Orientation	Horizontal	N/A
Temperature	50 C	Heated Disc
Disc Size	30 cm	Diameter
Solution A Concentration (Acidified Water)	pH = 1.5	N/A
Ratio of Flow Rates	20:1 (A:B)	N/A

Table 13. Fixed properties in the experimental setup of the production of nZVI nanoparticles [3].

Variable Property	Range	Optimal Setting
Total Flow Rate	0.0036 L/min - 0.018 L/ min	0.018 L/min
Feed Lines Separation	Center/5 cm/10 cm (Radially)	10 cm
Ratio of Flow Rates	6:1 / 8:1 / 12:1 / 16:1 / 20:1 (Acid Water:TTIP)	20:1
Disc Speed	400 RPMs - 1200 RPMs	1200 RPMs
Disc Characteristics	Smooth / Grooved	Grooved

Table 14. Variable properties in the experimental setup of the production of nZVI nanoparticles [3].

The TiO2 nanoparticles produced with this process have a mean diameter ranging from less than 1 nm to around 20 nm. The yield was above 90% for each run. The smaller the particle, the narrower the particle size distribution as well, but even the larger particles distribution was reasonable (ones with a 20 nm mean diameter only had particles from 10 nm to 30 nm, with 70%+ within +/- 5 nm). The nanoparticles produced in the STR were micron sized, compared to the nanoparticles produced by the SDR [3].

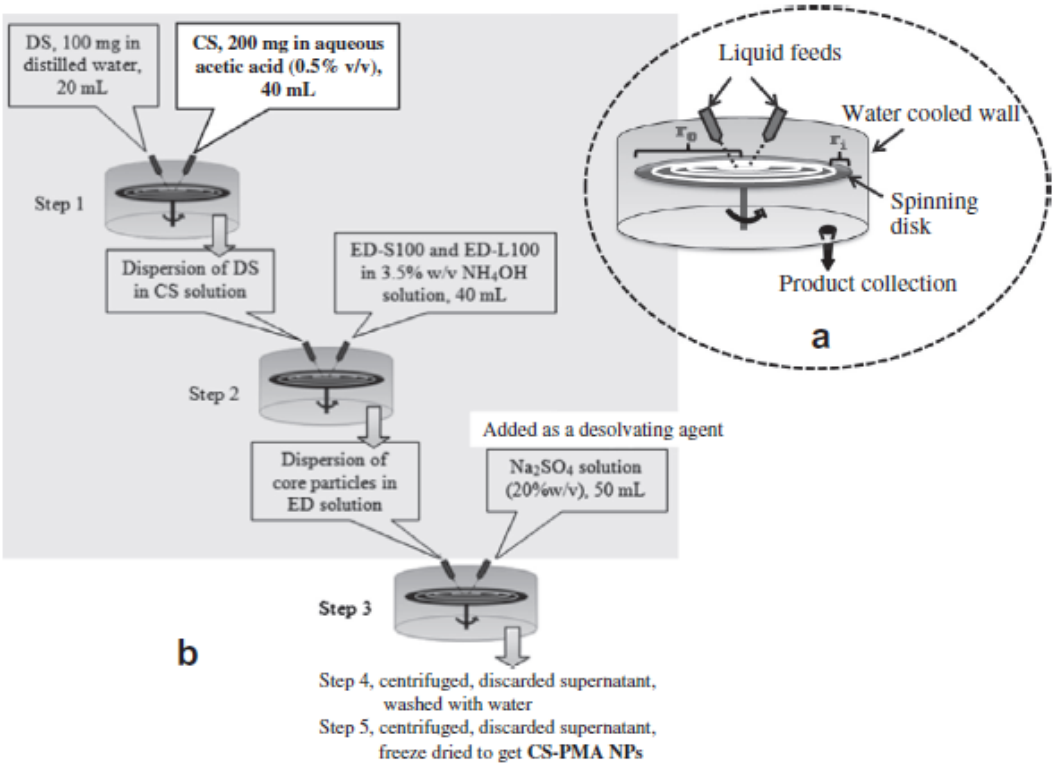
All the factors investigated were significant in determining the size and particle distribution of the TiO2 nanoparticles. Higher flow rates, farther from the center injection sites, higher feed ratios of acid water, higher RPMs, and a grooved disc all decrease mean diameter and narrowed the particle size distribution [3].

TiO2 nanoparticles are currently commercially used as pigments, cosmetics, pharmaceuticals, photocatalysts for the decomposition of pollutants, and as catalysts for metal oxidation and hydrogenation. Due to the high degree of accuracy (narrow PSD), range of sizes, and current commercial uses, TiO2 nanoparticles made by an SDR are worth looking into [3].

2.1.9 Magnetic Nanoparticles

This paper is a tad bit different than the rest. It's focus is on the production of TiO2 nanoparticles with a magnetic core and functionalized surface. An SDR is only used to make the magnetic core (SiO2/Fe3O4 nanospheres), and there is very little discussion how that is done. One can assume that it's a reactive precipitation of a ferrous solution with an oxygenated solution [20].

The more important aspect of this paper is that they successfully create TiO2 nanoparticles that are shown to work as photocatalysts and assist in the removal of phenol from a wastewater



stream. They are then easily removed via magnetic filtration. The TiO2 was added to these magnetic nanospheres via the sol gel method (which possibly could be copied over to an SDR process following the procedure in **Section 2.1.8**) [20]. One could most likely add different coatings to these nanospheres to produce magnetic nanoparticles for different applications .

While they don't discuss the process of producing magnetic nanospheres in detail, the paper shows a very interesting and worthwhile application of using an SDR to produce magnetic nanoparticles that perform their intended application well [20].

2.1.10 Specially Structured Chitosan Particles

This last article describes a more specialized process like the article beforehand. They used a multi-step SDR process to create, and then coat chitosan nanoparticles with slow release polymers and then pharmaceuticals. The experimental setup is seen in Figure 8 [10].

Figure 8. Experimental setup for the production of drug loaded chitosan nanoparticles [10].

The novelty of using chitosan as a drug delivery vehicle is its safety (non-toxic and biodegradable), targeting properties (focused absorption on inflamed tissue), and solubility in water and weak acidic solutions. This makes it especially effective at getting drugs to the colon and intestines, which is normally hard due to the required delayed release. It also would be able to reduce side effects from the drug being released in areas where it is unwanted [10] [20].

The particles that they made were controllable to a certain degree using the amount of the drugs loaded and the disc speeds used (controlling the size of the particles). They used a Design of Experiments layout to minimize the release of the drug in the areas that they didn't want it, and maximize in areas that they did. They ended up being able to create a particle that released < 10% of the drugs loaded on it in unwanted areas, and > 90% in the areas they did. This is much better than just taking the drug without a drug delivery vehicle, which has < 20% absorption where they want [10].

Since the particles made were incredibly useful, and the notion that this could be repeated for different pharmaceuticals, the idea of using SDRs to make pharmaceuticals and delivery vehicles is quite appealing [10].

2.2 Market Size and Pricing

So far, only the feasibility of the actual processes have been investigated, but if the materials produced don't have a market or realized use yet, the use of an SDR to make nanoparticles would be limited to academic research. Next, the market sizes and detailed uses of certain nanoparticles of interest are investigated. Market information is only provided for those materials that had detailed market information specifically to the nanoparticle material available (not bulk or other powders).

2.2.1 Silver

One of the most commercially feasible nanoparticle that has been demonstrated to be producible with a SDR is silver nanoparticles. It has a realized global market size of about $1 billion and a US market size of about $300 million. This comes out to about 700 tons per year. Notably, it accounts for about 50% of the global nanoparticle market in terms of US dollars [21] [22].

About 50% of this is through "Healthcare and Lifesciences" which would focus on its antibacterial and wound healing properties. Another 20% would be on "Textiles" would use its water repellency, breathability, anti-fungal, and UV protection to help make "smart textiles". The rest of the market is on using them for "Electronics", where they can be used in sensors and photovoltaic cells, and the "Food and Beverage" industry where it's used again for its antibacterial properties [22].

There has been a large push recently to produce silver nanoparticles using a more green method than before, which makes the process described in **Section 2.1.2** very appealing. The market is also supposed to have a compound annual growth rate (CAGR) of close to 13%, making it a good market to move into [22].

2.2.2 Magnesium Oxide

One of the smaller niche markets for nanoparticles that had available market information on it was for magnesium oxide nanoparticles. It has a realized global market size of about $30 million. This comes out to be about 110 tons per year [23].

Almost of all of this is used as fuel additives to increase fuel efficiency and in materials/ construction where it is added to materials due to its high hardness and low weight. One of the markets that are expected to see some increase in use is with airplanes where it would be used in composite materials on the plane [23].

Right now, China is able to produce the material cheaper than the rest of the world, most likely due to environmental considerations. When you add in that it is a rather small market, it is not advised to look into this material until the market grows larger [23].

2.2.3 Titanium Dioxide

The other more feasible nanoparticle material with an already realized use is titanium dioxide nanoparticles. It has a global market size of about $220 million. This comes out to be about 100,000 tons a year due to it's much lower price [24].

About 50% of this is used in cosmetics, paint, and coating. This is due to its UV blocking properties, with the main product actually being sunscreen. The next largest use is it as a catalyst in either metal oxidation/hydrogenation, or as a photocatalyst. Both of these uses usually use the rutile phase material which is considered easier to make. The other phase, anatase, accounts for the rest of the market (close to 25%) where it is used in electronics. The process described in **Section 2.1.8** originally makes rutile particles, which can be processed through heating into anatase particles [3] [24].

Along with a realized market, it has a compound annual growth rate of 7.7%. While lower than the silver nanoparticle market, it also has had a surge of patents and academic research being conducted with the material in the past 5 years that could cause a higher growth rate than expected [24].

2.2.4 Pharmaceuticals

In terms of nanoparticles, the last industry of interest that is currently viable for SDRs would be pharmaceuticals. There's a less defined market for nanoparticles in pharmaceuticals as there are many different types from actual drugs to drug delivery vehicles. Using the two compounds investigated in the proof of concept section, chitosan has close to a $1.5 billion global market size specifically for pharmaceuticals, and curcumin an over $20 million global market size specifically for pharmaceuticals. While these are not only for nanoparticle use, they give an idea of the possibilities of markets that could be moved into [25] [26].

2.2.5 Quantum Dots

Since this report started with a look into producing quantum dots with a SDR, I wanted to include a look the current market for quantum dots. In 2010, the global market for quantum dots was low, sitting at $67 million [27]. It was projected to have an amazing 59.3% compound annual growth rate, which was mostly realized and by 2016 it has become a $610 million global market (with the estimated CAGR it was predicted to reach $670 million by 2015) [28]. The current growth rate is estimated at 41.3% now for 2016 to 2021, predicting the global market to reach $3.4 billion by 2021 [28].

With this growth rate and predicted future market, it does seem like a very appealing market to pursue. But as discussed in the proof of concept section, it would require some novel research in the field to enter the market.

Currently most of this market is dominated by cadmium quantum dots which include cadmium selenide, cadmium sulphide, and cadmium telluride nanoparticles. Recently indium arsenide and silicon nanoparticles have entered into the industry and tend to be the focus of future research since cadmium is considered quite toxic and expensive. There have even been bans of heavy metal nanoparticles in general items [29] [30].

2.3 Focus and Summaries

Taking into account what was shown to currently be possibly with a SDR and what has a currently realized market, there seems to be a couple viable options to presently pursue.

Quantum dots don't seem to have been proven to work with SDRs, but I blame that more on information being withheld than it being impossible. Thus if one has the R&D budget, it'd be worth pursuing trying to accomplish the production of quantum dot materials.

Pharmaceuticals are a not well defined market, but it seems possible to use an SDR to make drug delivery particles and even end-use pharmaceuticals. Once again, it seems if one has the R&D budget that one could tinker with the idea and end up with a marketable product. The obvious issue is the high cost of entry with pharmaceuticals. Thus, a more apt focus would be on pitching the SDR to those who already make nanoparticles for pharmaceuticals as a lower cost/higher production method to something that is already established. Chitosan seems to be a great option as it has a huge market, proven characteristics, and research backings its use as a drug delivery vehicle.

Both silver and titanium dioxide nanoparticles have a realized and open market to enter with predicted growth and new applications coming out consistently. The cost to produce the materials is rather low as seen later in **Section 3** and the production ability seems high enough, especially with silver, that a company could actively pursue using an SDR to produce the nanoparticles with success. Since the proof of concept and idea is already detailed, there would be a low cost of entry into these markets as well. The revenue from such could be used to support R&D into quantum dots or pharmaceutical nanoparticles.

3. Areas of Focus

In this section I will go through the areas of focus and either make a business case or describe the areas for you to focus your pitches of the SDR on. I will try to summarize the previous information in a way that would help you make a case to someone producing the material to swap to a SDR or make a case to prospective producers so they can make an informed decision on the matter.

3.1 Silver

Silver makes for a very well-defined case study. The study shown investigates a relatively high level of production, using a mostly environmentally friendly process, and low cost materials. It also has a widely accepted pricing range depending on what size particle and purity of the product.

The process described in **Section 2.1.2** would produce silver nanoparticles reacting silver nitrate with glucose in a basic environment and using starch as a protecting agent to avoid agglomeration. The silver nitrate accounts for ~98% of the cost of the reactants, dwarfing the others by far. The rest of the reactants, starch, glucose, and sodium hydroxide are very cheap in the amounts required to drive the reaction. The total cost for reactants comes out to be about $0.92 for each gram of nanoparticles produced (prices sourced from an average of domestic suppliers on Alibaba). At a rate of 33 kg per day, that comes out to be around $11 million a year.

The process can produce nanoparticles with a narrow particle size distribution averaging anywhere between 10 nm – 40 nm as produced, and could be dispersed down to 5 nm – 10 nm. Since the particles are the only solid in the mixture, they are easily centrifuged and washed as described in the paper (water and acetone washes). As described in **Section 2.1.2** there would be a residual amount of starch on the surface of the nanoparticles resulting in silver nanoparticles with the purity of ~97%. Through heating the nanoparticles to 310 C, the starch went through pyrolysis and is easily removed from the surface of the particles. This is slightly out of the range of a commercial cooking oven, but to get an idea I found the cost to run an oven at ~250 C 24 hours a day to be $4,380 per year. For a safe estimate, I doubled it and rounded it to around ~$10,000 a year.

The other large cost in these types of processes is employees. On a cut-throat schedule of having one operator always there, a full-time 40 hours a week engineer, and a full-time 40 hours a week maintenance worker, it totals to about $436,000 a year. This includes benefits and additional costs of having staff.

If nanoparticles of 99% purity or higher can be produced anywhere in the range of 10 nm - 40 nm, they can be sold at a wholesale price of $3 a gram. To undercut the market to allow for entry I assumed a price of $2 a gram. This comes out to be about $24 million a year in revenue. As seen in Table 15, this comes out to about $12 million a year in profit. Referencing **Section 2.2.1**, a producer with this production rate would have a 1.56% market share of the global market.

Item	**Cost/Revenue ($/year)**
Reactants	-$11,000,000
Employees	-$436,000
Purification	-$10,000
Revenue	+$24,000,000
Profit	**+12,554,000**

Table 15. Breakdown of costs and revenue for the process of producing silver nanoparticles with an SDR.

There are more costs than I have detailed here, but this breakdown shows the process is reasonably profitable without requiring a large share of the market. Some additional costs to consider are additional processing to disperse the nanoparticles if sold that way, additional purification for high-purity applications, wastestreams (the silver nitrate would most likely be recycled), etc. This process however could also be accomplished with the SDR produced by Infinity Turbine. This means either the SDR could be pitched to current silver nanoparticles producers or those attempting the enter into the market.

3.2 Titanium Dioxide

The titanium dioxide's studies that I have read don't allow for easy scalability and thus it is harder to make a business case than it was for the silver nanoparticles. However, the study shown in **Section 2.1.8** does compare using a CSTR (the more conventional approach to making nanoparticles) with a SDR to produce the nanoparticles. Using this comparison, one can make a pitch to those making titanium dioxide with a CSTR that changing to a SDR would be a very economical choice.

As shown in Figure 9 the SDR is able to make much smaller particles, at a much lower energy cost than the CSTR. Also, the yield is substantially higher. This cuts down on purification and increases overall production. Finally, the residence time of the SDR is almost an order of magnitude larger (from a conservative 1 second for the SDR to 60 seconds for the STR). Since the method of production is the same and one can produce more, with a lower energy and purification cost, it provides for a reasonable pitch to anyone producing TiO2 nanoparticles through other methods.

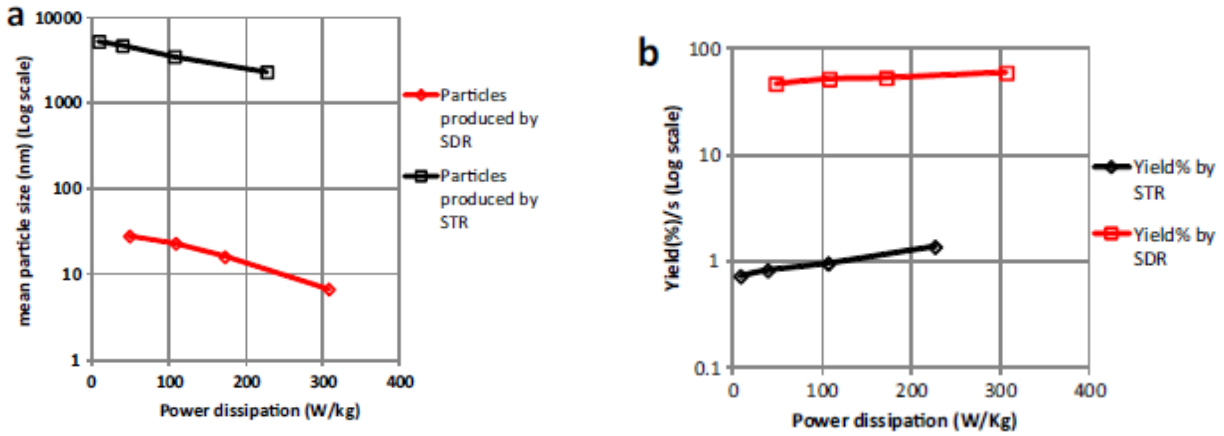


Figure 9. Graphs showing the amount of energy required per kilogram of titanium dioxide nanoparticles produced. (a) shows the energy in relation to the mean particle size. (b) shows the energy in relation to the overall yield of the process [3].

3.3 Pharmaceuticals

Pharmaceuticals won't have an easy business case either as it is more loosely defined than the other two markets due to the options available. However, pharmaceuticals are usually hindered by low production due to them being produced by small batch reactions and in this report it has been shown that certain drugs could be produced in a continuous fashion with high success and production rates [31].

I believe the focus should not be on end-use pharmaceuticals due to the slower acceptance of new methods because of FDA approval, but if someone is making a product to be used in the production of a drug (like a vehicle), there might be easier adoption if they can match the previous production quality. Since SDRs have been able to produce nanoparticles in a more controllable fashion and more narrow particle size distribution, I believe there is a case to be made for people swap over to using SDRs in the production of their materials.

3.4 Other Nanoparticles

Other than the nanoparticles discussed in the proof of concept section, there are two others that are widely used and have a rather large current market. These include gold nanoparticles and silicon based nanoparticles.

3.4.1 Gold

Gold nanoparticles have not been proven to be producible via a SDR, but they should easily follow the silver nanoparticle production process with a reduction of a gold solution over the disc of the reactor. The market for gold nanoparticles is already a billion dollar industry and is expected to reach $5 billion by 2020 with a CAGR of 24.7%. About 50% of the current market is based off of medical applications like imaging and cancer cell destruction [32].

This would be another great R&D option to pursue if the money is available since there is already a large market available to enter. 30% of the production also comes from the US due to stringent requirements around the quality of the nanoparticles and thus you could focus on pitching the SDR to domestic ventures [32].

3.4.2 Silicon Based

The final nanoparticle worth looking into would be silicon based nanoparticles. These would most likely be the best quantum dots worth looking into for a couple reasons.

They have little to no toxicity compared to cadmium nanoparticles which have been avoided in medical applications due to their high toxicity. Also, as stated before there are starting to be bans in using heavy metal quantum dots altogether [4] [30].

They also have better properties when it comes to certain electronics like batteries and sensors. For example, they have the highest lithiation capacity of any material known to man making it a coveted prize for Li-Ion battery manufacturers to incorporate into their batteries if degradation can be avoided [4].

Some ideas for production can be found in source [4] in section 2.3 “Chemical Techniques”. These production methods are shown already to work, but would be need to be adapted for SDR use. One example is the reduction of silicon halides with various reduction agents. It has been shown using various strength reduction agents, different size nanoparticles could be made [4].

If you would want to pursue making quantum dots with an SDR, I would focus heavily on silicon nanoparticles as that will be where most of the focus is on in the growth of the field.

4. Conclusion

This report ended up taking a different turn than originally planned, but altogether I believe it contains a lot of valuable information on the current known ability of using SDRs for nanoparticle production. I provided information about using SDRs to make nanoparticles, which could help someone who is trying to make novel nanoparticles, such as quantum dots, with an SDR, and provided ideas of current markets one could enter with your SDR if immediate revenue was needed.

Summarizing the current scene, I believe SDRs are a very new type of processing unit that have new applications being discovered every year. All the articles used in this report are under 10 years old, with the newest one being published this year due to most of the research on the topic being so new. While there is no publicly available information on using SDRs to make

quantum dots, I believe that it is possible and most likely is being optimized currently in the private market.

With the research I have conducted and summarized, someone looking to use your SDR to make quantum dots or other novel nanoparticles would be able to make informed decisions on operating parameters such as reactant concentrations, disc speeds/characteristics, flow rates, etc. and have a general idea of what the characteristics of the nanoparticle would.

Also, using this report, one could easily make a business case to use your SDR to start making silver nanoparticles which have a large current market. Titanium dioxide and pharmaceuticals are another good option to pursue, albeit should be entered with more caution. While the processes are possible with an SDR, the cost and production ability are less defined and thus might not be feasible.

Wrapping up, most of the markets discussed here are rapidly growing and are going to have new players entering consistently. With the right advertisement and focus, this could drive demand for your reactors. I would recommend focusing not explicitly on quantum dots, but on nanoparticles altogether. I'd also include specifics, like being able to make silver nanoparticles with a high production rate using a green process. Also, include all the possible nanoparticles I have listed here and keep a research search notification for new papers and patents on other nanoparticles made with an SDR to add. You never know which material is going to have the next great use. I'd also suggest if you have the R&D budget, looking into making silicon or cadmium nanoparticles with your SDR. Like you mentioned, having explicit proof that it works with your product would be a very great pitch. Although I'd be hesitant to release that information publicly if you're able to do so. If you can make them continuously and cheaply you might want to look into getting a patent yourself on the process.

Work Cited

[1] Reay, D., Ramshaw, C., & Harvey, A. (2013). *Process Intensification: Engineering for efficiency, sustainability and flexibility*. Butterworth-Heinemann.
[2] Khan, W. H., & Rathod, V. K. (2014). Process intensification approach for preparation of curcumin nanoparticles via solvent–nonsolvent nanoprecipitation using spinning disc reactor. *Chemical Engineering and Processing: Process Intensification*, *80*, 1-10.
[3] Mohammadi, S., Harvey, A., & Boodhoo, K. V. (2014). Synthesis of TiO 2 nanoparticles in a spinning disc reactor. *Chemical Engineering Journal*, *258*, 171-184.
[4] Huan, C., & Shu-Qing, S. (2014). Silicon nanoparticles: Preparation, properties, and applications. *Chinese Physics B*, *23*(8), 088102.
[5] Farahani, H. B., Shahrokhi, M., & Dehkordi, A. M. (2017). Experimental investigation and process intensification of barium sulfate nanoparticles synthesis via a new double coaxial spinning disks reactor. *Chemical Engineering and Processing: Process Intensification*, *115*, 11-22.
[6] Chang, M. H., Liu, H. S., & Tai, C. Y. (2011). Preparation of copper oxide nanoparticles and its application in nanofluid. *Powder technology*, *207*(1), 378-386.
[7] Tai, C. Y., Tai, C. T., Chang, M. H., & Liu, H. S. (2007). Synthesis of magnesium hydroxide and oxide nanoparticles using a spinning disk reactor. *Industrial & engineering chemistry research*, *46*(17), 5536-5541.
[8] Tai, C. Y., Wang, Y. H., & Liu, H. S. (2008). A green process for preparing silver nanoparticles using spinning disk reactor. *AIChE journal*, *54*(2), 445-452.
[9] Liu, H. S., Wang, Y. H., Li, C. C., & Tai, C. Y. (2012). Characterization of AgI nanoparticles synthesized in a spinning disk reactor. *Chemical Engineering Journal*, *183*, 466-472.
[10] Huanbutta, K., Sriamornsak, P., Luangtana-anan, M., Limmatvapirat, S., Puttipipatkhachorn, S., Lim, L. Y., ... & Nunthanid, J. (2013). Application of multiple stepwise spinning disk processing for the synthesis of poly (methyl acrylates) coated chitosan–diclofenac sodium nanoparticles for colonic drug delivery. *European Journal of Pharmaceutical Sciences*, *50*(3), 303-311.
[11] Horiba Scientific. (2017). *What is a Nanoparticle?* Retrieved from: http://www.horiba.com/scientific/products/particle-characterization/applications/what-is-a-nanoparticle/
[12] Yu, P., Yao, Y., Wu, J., Niu, X., Rogach, A. L., & Wang, Z. (2017). Effects of Plasmonic Metal Core-Dielectric Shell Nanoparticles on the Broadband Light Absorption Enhancement in Thin Film Solar Cells. *Scientific Reports*, *7*(1), 7696.
[13] Wu, J., Yu, P., Susha, A. S., Sablon, K. A., Chen, H., Zhou, Z., ... & Rogach, A. L. (2015). Broadband efficiency enhancement in quantum dot solar cells coupled with multispiked plasmonic nanostars. *Nano Energy*, *13*, 827-835.
[14] Ramírez, H. Y., Flórez, J., & Camacho, Á. S. (2015). Efficient control of coulomb enhanced second harmonic generation from excitonic transitions in quantum dot ensembles. *Physical Chemistry Chemical Physics*, *17*(37), 23938-23946.
[15] Stoller, M., Vuppala, S., Matarangolo, M., Vaiano, V., Sannino, D., Chianese A., Cianfrini, C., (2017) About a novel production method for N-doped magnetic nanocore nanoparticles of titania by means of a spinning disk reactor. *Chemical Engineering Transactions,* Vol. 60, 2017
[16] Jia, L. (2005). Nanoparticle formulation increases oral bioavailability of poorly soluble drugs: approaches, experimental evidences and theory. *Current nanoscience*, *1*(3), 237-243.
[17] Bertolini, J. C., & Rousset, J. L. (2008). Reactivity of Metal Nanoparticles. In *Nanomaterials and Nanochemistry* (pp. 281-304). Springer Berlin Heidelberg.
[18] Hu, M. Z., & Zhu, T. (2015). Semiconductor nanocrystal quantum dot synthesis approaches towards large-scale industrial production for energy applications. *Nanoscale research letters*, *10*(1), 469.
[19] Vilardi, G., Stoller, M., Verdone, N., & Di Palma, L. (2017). Production of nano Zero Valent Iron particles by Means of a Spinning Disk Reactor. *CHEMICAL ENGINEERING*, *57*.

[20] Wang, J. J., Zeng, Z. W., Xiao, R. Z., Xie, T., Zhou, G. L., Zhan, X. R., & Wang, S. L. (2011). Recent advances of chitosan nanoparticles as drug carriers. *International journal of nanomedicine*, *6*, 765.
[21] Pulit-Prociak, J., & Banach, M. (2016). Silver nanoparticles–a material of the future…?. *Open Chemistry*, *14*(1), 76-91.
[22] Global Market Insights. (2015). *Silver Nanoparticle Market Size.* Retrieved from: https://www.gminsights.com/industry-analysis/silver-nanoparticles-market
[23] Business Wire. (2016). *Magnesium Oxide Nanoparticle Market.* Retrieved from: http://www.businesswire.com/news/home/20160215005634/en/Global-42-Billion-Magnesium-Oxide-Nanoparticle-Market
[24] Mordon Intelligence. (2017). *Titanium Dioxide Nanomaterials Market*. Retrieved from: https://www.mordorintelligence.com/industry-reports/titanium-dioxide-nanomaterials-market
[25] Grand View Research. (2017). *Chitosan Market Estimates and Trend Analysis*. Retrieved from: http://www.grandviewresearch.com/industry-analysis/global-chitosan-market
[26] Global Market Insights. (2017). *Curcumin Market Size*. Retrieved from: https://www.gminsights.com/industry-analysis/curcumin-market
[27] bccResearch. (2011). *Quantum Dots: Global Market Growth and Future Commercial Prospects*. Retrieved from: https://www.bccresearch.com/market-research/nanotechnology/quantum-dots-market-prospects-nan027c.html
[28] Research and Markets. (2017). *Quantum Dots Market*. Retrieved from: https://globenewswire.com/news-release/2017/02/21/925807/0/en/3-4-Billion-Quantum-Dots-Market-Global-Market-Report-and-Future-Commercial-Prospects-2021.html
[29] Allied Market Research. (2014). *Quantum Dots Market*. Retrieved from: https://www.alliedmarketresearch.com/quantum-dots-market
[30] Electronics 360. (2017). *European Commission Moves to Ban the Use of Cadmium in TVs and Displays*. Retrieved from: http://electronics360.globalspec.com/article/9507/european-commission-moves-to-ban-the-use-of-cadmium-in-tvs-and-displays
[31] MIT Technology Review. (2012). *Breakthrough Offers a Better Way to Make Drugs*. Retrieved from: https://www.technologyreview.com/s/506511/breakthrough-offers-a-better-way-to-make-drugs/
[32] Radiant Insights. (2012). *Gold Nanoparticles Market*. Retrieved from: https://www.radiantinsights.com/press-release/global-gold-nanoparticles-market