APPLICATION SPOTLIGHT

Liquid Phase Exfoliation of Graphite to Graphene

DeBEE High Pressure Homogenizers Use Three Forms of Energy to Disrupt Agglomerated Materials.

Graphene processing requires a lot more than particle reduction. Reliable graphene processing also renders precise layer counts and enhances the stability of graphene-based nanofluids. Only Pion's DeBEE brand ultra High-Pressure Homogenizers (uHPH) have **our** patented Emulsifying Cell (EC) capable of delivering these properties. The EC has a highly flexible configuration allowing process optimization for individual projects or a wide variety of different materials and formulations.

The proprietary combination of forces in our EC technology ensures not just the smallest particle reduction of any sample, but scalability and high yield. The design of our flexible, modular system is easy to use, clean, maintain and service, allowing custom processing for any type of application so that results are always scalable. With our equipment, flake graphite can be easily transformed into useable graphene in less time and for less money, enabling you or your customers to successfully use this versatile material.

Our truly unique technology can create several beneficial properties in graphene:

- **Homogenization**, the incorporation of graphene into products.
- **Scalability** of liquid-phase graphene products.
- **Stability** of graphene dispersions not possible through conventional means, tolerability, and convenience.

Graphene processing requires a specific, tailored, and reproducible approach most equipment cannot provide. DeBEE uHPH enables users to carefully exfoliate graphite and reduce layers, while maintaining a high aspect ratio and cell morphology. Customizing and selecting forces further improves efficiency.

Exfoliation of graphite is achieved with the following mechanisms within a DeBEE uHPH

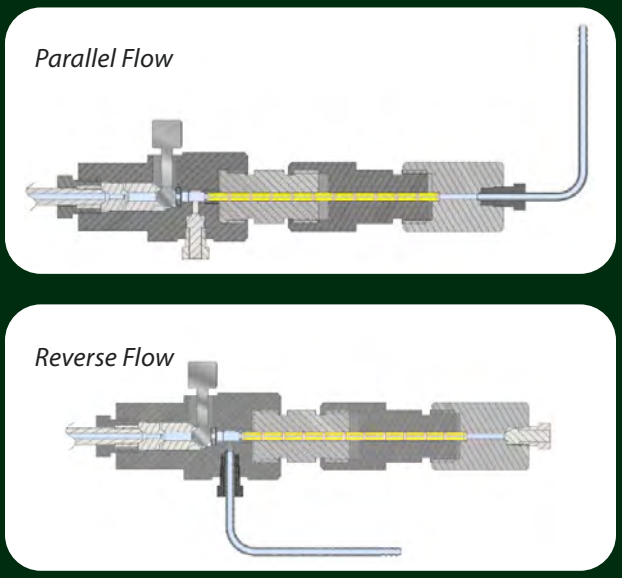
- **Compressible Flow Exfoliation:** Graphite is forced through a small orifice (nozzle) at up to 45,000 psi. Pressure and orifice sizes are adjustable.
- **High Shear:** The graphite slurry is forced through a narrow tube (reactor) where controllable shear force reduces layer counts.
- **Cavitation:** The configuration of the reactors influences the environment experienced by the graphite. This may include alternating orifice sizes which can induce micro cavitation of bubbles or microjets, and stress waves which separate graphite layers.
- **Collision Exfoliation:** The reverse flow mode, returns graphite into the initial flux stream, inducing particle on particle collisions. The force is tuned based on the orifice sizes, flow path, and pressure.
- **Chemical Exfoliation:** Control over the high-stress environment within the reaction cell, and the ability to incorporate multiple materials throughout the process can functionalize graphene.
- Optional **dual injection stream** capability expands development opportunities. Effectively mix materials within the liquid-phase reaction chamber.
- Colloidal assemblies through apolar and polar solvent droplet formation.

This versatility empowers a market disruptive area where DeBEE uHPHs excel. DeBEE uHPH configurations can be modified to create specific products, allowing businesses to have patented procedures that are extremely likely to be novel.

DeBEE uHPH enables optimization of graphene processing using the following variables

- **Flow Patterns:** PF = Parallel Flow, RF = Reverse Flow, DF = Dual Feed.
- **Absorption Cell Patterns:** Number and Size of Reactors
- **Operating Pressure:** Up to 45,000 psi (3100 bar) and Adjustable Back Pressure
- **Nozzles Sizes:** Range from 0.1mm - 0.25mm
- **Heating/Cooling Setups:** Pre & Post Cooling

Solvent and additive choices are important for the stability of graphene dispersions. The product contact parts of the DeBEE uHPH are chemical resistant. If incompatibilities arise, suitable parts may be exchanged.



Particle size distribution can be precisely controlled to meet different application needs. For example, some clients require large, three-layer graphene particles that minimize grain boundaries for electronic applications, while others need single-layer graphene particles for nano-graphene uses. Processing forces can be adjusted accordingly—ranging from levels that target weak intermolecular van der Waals forces to higher energies capable of disrupting strong intramolecular covalent intramolecular interactions.

Dual Feed

A second in-feed option is available with DeBEE technology. This introduces the possibility of separating the ingredients of a formulation. There are several opportunities created by this configuration

- Ingredients that either need to avoid the highest energy zone, or don't require it, can be input after the nozzle, avoiding some of the shear and cavitation. These ingredients are still efficiently mixed into the stream as they pass through the reactor sequence.
- Sometimes ingredients should not be combined until they can be mixed with high energy. The DeBEE Dual Feed option keeps reactive ingredients separated until they can be intimately mixed in milliliter quantities. This avoids premature reactivity and destabilization of the premix.
- Add nanoparticles (e.g. ZnO) to integrate with graphene, creating new products. For example: new catalysts or modified electronic structures.
- The Dual Feed option can be used to simply increase the throughput capacity of the system.

An example of the Dual Feed option in use on a Nano DeBEE.

Some models allow for certain powders to be incorporated directly into the mixing stream.

Modular EC configuration for more economical maintenance

Wear items can be easily and inexpensively replaced by the user. Unlike homogenizers with expensive, complicated valves, or sealed, non-serviceable Interaction Chambers, the DeBEE EC can be disassembled down to component level. A worn part can be replaced in 5 minutes and cost around $20 USD.

Pion provides solutions from R&D (10's of milliliters) to large-scale manufacturing. Whether you are beginning processing graphene and need a viable experimental process, working on new products or applications, or scaling existing products more efficiently, Pion provides equipment to achieve your goals and accommodate growth.

Pion recognizes the widespread application of 2D materials and their potential societal impact. As companies innovate and produce products that enable technological advancement, a need arises for proven and dependable equipment that achieves efficient and scalable results. Pion is uniquely capable of providing these solutions and welcomes opportunities to assist in developing new technologies.

We offer unparalleled processing versatility for the liquid exfoliation of graphite that can be foundational to many products and patents. The liquid-phase exfoliation of graphene and other 2D materials can be created, scaled and commercialized through the utilization of Pion's DeBEE uHPH technology.

Further Reading

A study[1] looked at temperature, number of passes, and pressure on the exfoliation expanding to other 2D materials. This study excluded other reactor combinations, which offer many more configuration and processing possibilities.

Emergent high conductivity in size-selected graphene networks

Measuring the Surface Energy of Nanosheets by Emulsion Inversion

Blog Posts to Explore - Pion Inc

Resource Library - Pion

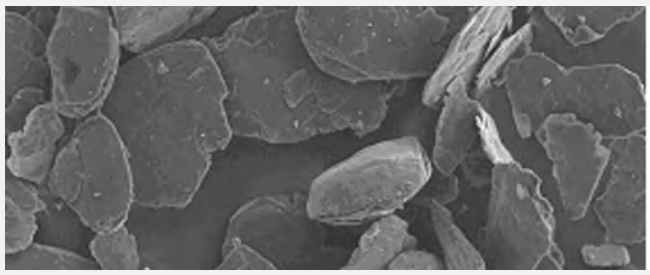
Reference

1. M. J. Large *et al, Adv. Mater. Technol.*, 5, 2000284 (2020)

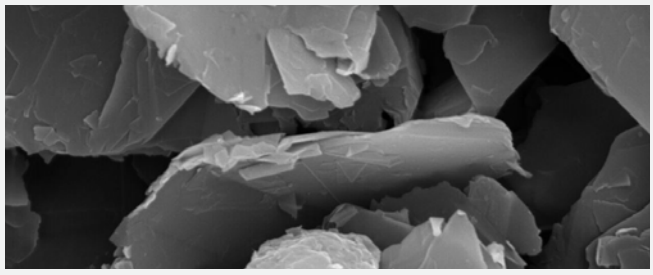
Applications

Companies involved in the following fields would benefit from Pion's individual approach to homogenization. We are always open to exploring emerging applications.

- Conductive ink. Graphene paste can reach conductivity levels required for electronic applications (e.g., 28 kS m^{-1}). Conductive graphene inks can be used for photovoltaics, biomedical sensors, flexible displays, automotive applications, RFID, and PCB technologies.
- Battery development.
- Integrate graphene into polymeric matrix coatings.
- Cement and concrete. DeBEE technology can exfoliate and stabilize graphene in aqueous solvent at high throughput.
- Scale-up of lab scale inventions.
- Improve and upscale surface-engineered catalysts.
- Graphene-enhanced sensors.
- Wearable graphite e-textiles.
- Environmentally-friendly graphene production.



Graphite: Exfoliated Nanostructures - Precursor 90x Mag



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