Development of Hydrocyclones for Use in Plastics Recycling

A Summary Report of Research Sponsored by
the American Plastics Council

Submitted by

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Executive Summary

Objective

Some of the major challenges facing the recovery of plastics from durable products such as automobiles, computers, and appliances are the separation of dissimilar plastics from one another and the removal of many non-plastic contaminants that cannot be removed using dry separation techniques such as magnetic removal or air classification. The principal technique for removal of these materials is density sortation.

One of the most promising density-based separation techniques under investigation by the American Plastics Council (APC) in collaboration with MBA Polymers involves the use of hydrocyclones in a water-based density sorting system. The objective of this study was to determine the effectiveness, operational parameters and limitations, and process characteristics of hydrocyclones when used to purify recycled plastic flake.

Approach

The project began with an investigation into the history of hydrocyclones, including their past and current uses and the fundamentals of their operation. A study of the characteristics of engineering plastics used in durable products was done to determine ways in which plastics are unique from other materials commonly processed by hydrocyclones. This led to a detailed study of the configurational variables of hydrocyclones, such as barrel diameter, vortex and apex aperture, with regard to plastics recycling. It then became necessary to develop metrics for the success of plastic separations that would clearly represent areas where hydrocyclones have strengths and weaknesses when processing plastic flake from durable goods.

Major Findings

In the early investigations it became clear that hydrocyclones offered many advantages over other density-based separation techniques, namely; cost, throughput, allowable particle size range, and space requirements.

There are a number of configurational variables that must be understood and controlled in order to make accurate separations with hydrocyclones. Barrel diameter must be sized based on an inverse relationship of throughput versus separation accuracy. Larger diameter hydrocyclones will generate higher throughputs, but separation accuracy will be sacrificed. Generally, for durable goods, the smallest size hydrocyclone barrel diameter is 6-inch to avoid material bridging without the need for extensive size reduction. This size unit will operate in a range up to 5,000 lb/hr providing an accurate separation. The largest unit under test at MBA Polymers is a 15-inch barrel diameter, which can provide more than 10,000 lb/hr. Two other important dimension parameters that must be properly sized are vortex finder diameter and apex diameter. These two critical dimensions control the split ratio of fluid to "lights" or "heavies", and differ greatly in plastics recycling use from many of the other applications for which hydrocyclones are used, such as mining.

Inlet pressure is a parameter that must be properly established when using hydrocyclones because it effects proper vortex formation and fluid flow within the hydrocyclone. This parameter is primarily established by the pump used in the system and can sometimes be used to fine tune a separation, although this parameter is often held constant once properly established.

Two methods for metering the success of hydrocyclone separations were implemented; partition curves, and an experimental design. The proper use of a partition curve allows for easy and understandable graphic representation of a hydrocyclone separation. Ideally, partition curves should have a steep slope across the area of intended separation. This indicates a very precise separation. Under the test conditions used for these data, utilizing partition curve analyses, single-stage hydrocyclones were seen to yield good separations at a density differential of approximately 0.025 g/cc.

An iterative experimental design was used to more accurately gauge the areas of successful hydrocyclone separation. The Box-Behnken method was selected. This mathematical modeling method was used to illustrate the most effective separation combination for a 6-inch hydrocyclone.

Conclusions

Hydrocyclones are an economical and effective tool for separating mixed durable plastics, and for removing many contaminants from a target plastic. The motive force for effecting hydrocyclone separations is density differential. The greater the difference in density, the higher probability of separating two dissimilar components. The shape of the particles to be separated in a hydrocyclone is also an important consideration. Since one hydrocyclone cannot guarantee close-tolerance separations, it is good practice to install hydrocyclones in series.

Introduction

The American Plastics Council (APC) has funded research into various areas relating to the mechanical recycling of plastics, including rapid plastics identification, size reduction, paint and coating removal, and separation technology. MBA Polymers, Inc. (MBA) has been involved with APC in all of these projects because the technologies are interrelated and complementary and the company has made a commitment to be a world leader in technology for the recovery of plastics from end-of-life durable products. MBA also operates a pilot recycling facility in Richmond, California to develop and demonstrate various recycling technologies and APC has been a key sponsor.

The model investigated by APC and MBA to recover plastics from durable goods using a mechanical recycling approach involves the following broad steps:

1. Plastics identification at the part level to effect a “coarse sorting”
2. Multiple-step size reduction to reduce the parts to particles for ease of handling in subsequent steps and to liberate the various materials from one another
3. Separations based on differences in the physical properties, physical characteristics and chemistries of the various materials

This report covers a specific area of research directed at improving the effectiveness of the separation stage of the operation: separations based on differences in material densities.

The most widely used and accepted techniques to separate mixed plastics are based on density because many plastics differ sufficiently in this material property. It can be used to separate polymers within the same family containing different additives in many cases. As these techniques are based on differences in a bulk material property, they are more predictable and reliable than separation techniques exploiting only surface-sensitive properties that can more easily vary with surface contamination such as dirt, oils, coatings, etc. and with environmental exposure such as UV degradation or oxidation. It should be pointed out, however, that density is not completely adequate to separate all plastics from one another (and indeed not all other types of materials from plastics) because different materials in a mixture may have densities that are too similar. Therefore, other separation techniques such as froth flotation and electrostatics may be beneficial even though they are sensitive to surface variations.

While the most basic density-based separation approach, sink-float tanks, require no special expertise to operate and little in the way of capital investment, they suffer from low throughputs, material wetting problems, and significant floor space requirements. Experience with sink-float tanks was obtained through several years of research carried out at the first mechanical recycling pilot line partially sponsored by APC. It was designed through a joint effort between APC, MBA, and wTe Corporation, and was operated by wTe in Boston, Massachusetts. It employed two sink-float separation systems based on auger-style classifiers.

Centrifuges perhaps represent one of the most sophisticated density separation tools, and can make very accurate separations at reasonably high throughputs. The primary drawback to centrifuges is their relatively high purchase and maintenance costs. Furthermore, only rather small particles can be fed to most centrifuges, so size-reduction expenses can be high as well. However, the high centrifugal forces can overcome particle shape effects.

Hydrocyclones lie between sink-float tanks and centrifuges with respect to cost and complexity. They represent an excellent density separation tool because they are relatively inexpensive, require very little space, suffer from fewer material-wetting problems than sink-float systems, and most importantly can be operated at extremely high throughputs. A single 10-inch cyclone can theoretically sort materials at rates in excess of 5,000 pounds per hour. Though multiple stages and pumps are usually required for challenging separations, the overall capital costs can be very reasonable particularly if water alone is used as a separation medium.

The table below shows a rough estimate of cost and throughput capacity comparisons for hydrocyclones, centrifuges, and sink-float systems.[1] Only costs associated with the separation units and necessary associated equipment such as pumps, piping, and slurry tanks are shown. Other items are not included, such as water treatment, dewatering, drying, screening, conveying, electrical, and mechanical installation costs. Each of the systems discussed has some variability in capacity that naturally changes the cost of the system, and the capacities can change dramatically depending on the form of the material being processed. The costs shown reflect the capacity given.

	Hydrocyclone System	**Centrifuge System[2]**	**Sink-Float Tanks**
Cost ($K)	30-60	450-650	15-50
Throughput capacity (lb/hr)	5,000 - 10,000	1,000 - 3,000	1,000 – 2,000

Hydrocyclones have been used for many years in dewatering and particle sizing applications in mining, waste management, and other industries. They cannot compete with more efficient separators like sedimenting centrifuges or filters for very fine particles, but with coarser solids the cost advantage of hydrocyclones makes them very attractive.[3]

Hydrocyclones have been used in simple plastic separation processes primarily using water as the medium, but their operation has not been well understood for this application. As noted above, these devices were originally designed simply to remove solids from liquid streams in wastewater treatment, mining, and agricultural applications. Major manufacturers of these devices, admit that they do not understand all of the issues associated with their use in plastics separation processes, which may partially explain their limited use in this application.

APC decided to support research in this area due to the limited amount of published information and the potential for increased separation capabilities for a wider range of post-use plastics compared to sink-float systems. APC collaborated with MBA Polymers based on the company's comprehensive work in the area of mechanical recycling of plastics from durable goods and a proposal it submitted targeted at that specific application.

Extensive testing of the fundamental performance of hydrocyclones for the separation of plastics was carried out. Initial testing was performed on a hydrocyclone test stand constructed at its research center located in Berkeley, CA. The test stand could accommodate up to three hydrocyclones and was used to demonstrate the cyclone capabilities, and experiment with new concepts. The next generation design was then built to test the most promising approaches suggested from the test stand studies. The research has sought to elucidate the fundamental parameters of the cyclone and to demonstrate new configurations that are more efficient. Areas of study included the use of:

- variable flow/pressure control
- variable apex and vortex combinations
- multi-step cyclones
- elevated cyclones
- separation curves
- sink-float separators

This research has led to a greater understanding of the capabilities and fundamental operating parameters for hydrocyclones, and has been used to help design a pilot separation line, the purpose of which is to demonstrate the application of hydrocyclone separations to a wide variety of plastic recycle streams. This report should stimulate a broader industry evaluation of hydrocyclones as a technically sound and cost-effective approach to plastics' separation and recovery for mixed post-use streams.

Hydrocyclone History and Fundamentals

History

The idea of using centrifugal acceleration for separation purposes was first applied to the problem of removing dust from air streams. In 1885, patents were granted for such a device in the United States and Germany to the Knickerbocker Company, USA.[4]

Bretney patented the application of the air cyclone to liquid streams in 1891.[5] The first recorded use of a hydrocyclone was by an American phosphate company in 1914, but the hydrocyclone did not see widespread industrial application until decades later. In 1939, M.G. Driessen described an application of the hydrocyclone to the dewatering of a water/sand slurry in a coal industry application.[6] For this application, the cyclone worked very well.

In the 1940s, the hydrocyclone began to see use as a density separation device in both the coal and pulp/paper industries. The device worked well in both of these applications, primarily because of the large difference in density of the two materials that were being separated. In the coal industry, it was desired to separate rock (s.g. ≈ 2.7) from coal (s.g. ≈ 1.3), and in the pulp and paper industry the hydrocyclone was used to separate sand (s.g. ≈ 2.2-2.6) from paper pulp (s.g. ≈ 1.1). In these applications, it was easy for the hydrocyclone to perform well as a density separation device. Because of success in these fields, the use of hydrocyclones grew quickly. The 350+ articles that were published between 1949 and 1957 evidence the high level of interest in hydrocyclone separation.[7]

The basic design of the hydrocyclone has not significantly changed since the early acceptance of the hydrocyclone as a standard industrial process.

Fundamentals

A hydrocyclone transfers fluid pressure energy into rotational fluid motion. This rotational motion causes relative movement of materials suspended in the fluid thus permitting separation of the materials from one another.[8]

A schematic of a hydrocyclone is presented in Figure 1. The mixed fluid enters tangentially at the inlet, which causes the material to rotate within the vessel and ultimately to form a vortex. As this vortex of fluid spirals within the cyclone, heavier materials are forced outward by centrifugal force and down from the barrel section into the cone section. The materials more dense than the fluid flow down the inner wall and exit through the apex and out the underflow port with a portion of the fluid. Lighter materials are swept into the center vortex by inward fluid motion, carried vertically up through the vortex finder, and out through the overflow port with the majority of the fluid.

The outlet for the bulk of the fluid is usually located near to or on the axis of the vessel such that the rotating fluid is forced to spiral towards the center to escape. A rotational motion has thus built into it an inward radial motion. Particles of a suspended material consequently have two opposing forces acting on them, one in an outward radial direction due to centrifugal acceleration, and one in an inward radial direction due to the drag force of the inward moving fluid.

The magnitude of these forces is dependent on the physical properties of both the fluid and the suspended material (e.g., size of particles, shape of particles, density of particles and of fluid, and viscosity of fluid). These properties can consequently effect the separations of one material from another or of a single material from the fluid.[9]

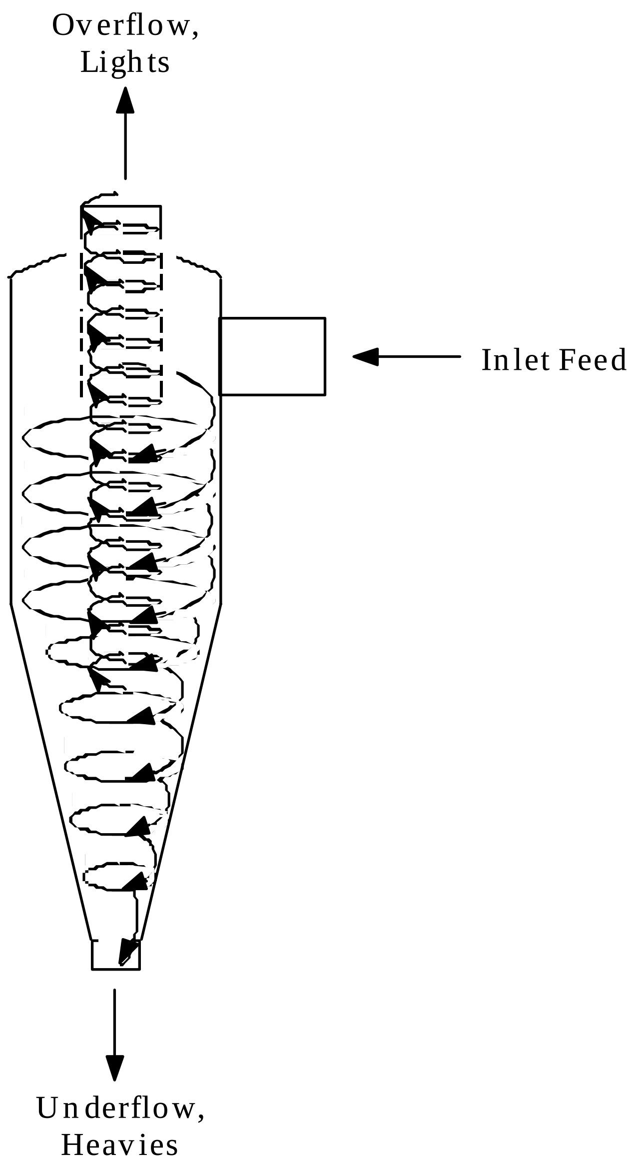


Figure 1. Schematic representation of spiral flow in a hydrocyclone.

Plastic Sorting Challenges for Hydrocyclones

Much of the conventional wisdom developed from the use of hydrocyclones in other industries can be applied to plastic separation. There are two additional complications, however, in the sorting of plastics:

1) the tendency for recycled plastic particles from granulated parts to have a plate-like shape, and
2) the density difference between dissimilar plastics is often very small (usually much closer than the examples mentioned earlier).

Particles are actually sorted in a cyclone based on settling velocity in a turbulent fluid. When approximately spherical particles of like-density are sorted (classified) in water, as in mineral benefaction, the coarse particles settle more rapidly and are concentrated in the underflow. Fine particles are also slightly concentrated in the underflow but the cyclone is configured to have a very small apex so very little of the water and fines exit through the apex. Since nearly all of the water is designed to exit through the overflow, most of the fines report here. The coarse particles, which are significantly concentrated in the underflow, are thus sorted from the fines and the majority of the water.

In the case of plastics, very coarsely ground particles are usually plate-like and may report to the overflow regardless of density. They may even be completely eliminated from the underflow if they are sufficiently large. The water exiting the apex has an extremely high rotational velocity component and can throw flaky pieces to the center toward the rising column that exits through the vortex. In summary, the smooth flow of flaky dense particles is disrupted and they are "bounced" into the overflow.

The plate-like character of recovered plastic materials diminishes as they are ground more finely and the particle size approaches the wall thickness of the original part. This plate-like character may be described as the length to thickness ratio or L/T. A high L/T represents a flaky particle; and an L/T equal to one represents a cube (or sphere).

Settling Experiments

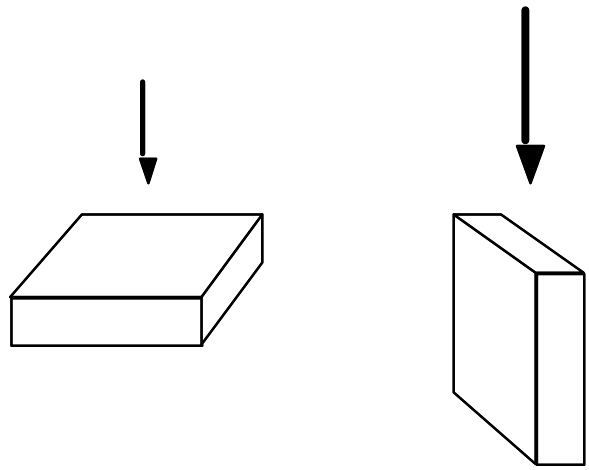
Laboratory investigations were undertaken to determine what factors most significantly effected terminal settling velocity in a calm fluid. These experiments measured the settling velocities of squares cut from three different thicknesses of injection molded specimens of two different plastic types. Large (1/2 in.) and small (1/4 in.) squares were cut from the three different thicknesses (1/4, 1/8, and 1/16 in.) of specimens in each variety of plastic to yield a total of 12 different varieties of squares. The small, thick squares of each polymer type were approximately cubic in shape.

The plastics used were High Impact Polystyrene (HIPS) (density = 1.045 g/cc) and Ignition Resistant HIPS (IRHIPS) (density = 1.17 g/cc). Results from six tests using each type of small square and three of each large square were averaged to yield the final data. The data were quite repeatable and some general conclusions can be drawn about factors that effect particle settling velocity.

When a square settles slowly its largest area is perpendicular to its motion. As terminal velocity is increased (by increasing the density differential driving force, for example), it will begin to rock back and forth like a leaf settling in air. If velocity increases still further the square will spiral downward, and at maximum velocity it will fall end down exposing its minimum area to the moving fluid. Particles settling slowly move with their longest dimension perpendicular to their downward movement. Particles that are moving very fast through a fluid do so with their longest dimension parallel to their movement. In short, particles are aligned by flow. See Figure 2.

In a calm fluid, wall thickness is the determining factor for settling velocity; size is not. The experimentation yielded curves for velocity, which were in each case naturally grouped by particle thickness. Small particles often settled just as fast as large particles if they had the same minimum dimension (thickness).

The fluid in a hydrocyclone is not calm and as the pressure drop increases the flow becomes increasingly turbulent. The turbulence does not change the rate at which cubic particles settle through the fluid (toward the wall in the case of a hydrocyclone), but high L/T particles are dramatically affected. At low turbulence levels, platy particles will align with the rotational flow as a fast settling particle and so settle toward the wall as a slow settling particle. As turbulence increases one would expect their settling rate toward the wall to increase as they begin to roll into orientations that provide less resistance to their radial movement. This behavior has been observed in a stirred tank. However, as turbulence levels increase still further, platy particles in a cyclone are likely bounced off of the walls and back into the center where the predominant flow in the cyclone is upward and out through the vortex finder. Platy particles can report to the overflow even if they are significantly denser than the fluid.



A) Slow settling particle B) Fast settling particle

Figure 2. Particle settling orientation in a calm fluid.

It has been observed that high L/T ratio particles act unpredictably and this poses a serious concern when optimizing hydrocyclone performance. Larger cyclones are favored when particles are large because of the decreased tendency for high L/T particles to report erroneously.

Particles that have one dimension very much greater than the other, such as needles or slivers, show a radical departure from theoretical performance in a cyclone due to the ease of misclassification. Within what can be a small volume of liquid, there are liquid streams that flow in many directions. Long particles can, therefore, be readily entrained in the wrong stream. Equally, the existence of shear in the liquid "confuses" the long particle, one end of which is propelled at a different velocity than the other.[10] Increasing the diameter of the hydrocyclone lessens this effect.

Hydrocyclone Configurational Variables

An investigation was undertaken to determine the most important parameters that control how hydrocyclones perform separations so the fundamental principles that govern their operation could be better understood. The configurational aspects of a cyclone that can be varied are the barrel section diameter and the sizes of the three apertures: inlet orifice, vortex finder, and apex.

Diameter

Hydrocyclones are available in a wide range of barrel diameters, from less than 1/2 inch to more than 50 inches. The barrel diameter is normally used to define the hydrocyclone size. This choice is partly governed by the size of solid material that the system is expected to encounter and by the design capacity of the system. Generally, the larger the feed particles to be separated, the larger the cyclone. Pressure drop across the cyclone is inversely proportional to the diameter of the barrel and the centrifugal force of separation increases with increased pressure drop. In other words, the force of separation is greater for smaller cyclones.

In conventional mining applications for hydrocyclones, the common separation focus is to remove coarse material from fine material. A 50% cutpoint (the point at which half of the material reports to the underflow and the other half to the overflow) is established that defines the size of particle to be targeted for classification. This is used to help size the cyclone. The cutpoint (d50) is proportional to the diameter of the unit. As the barrel diameter decreases, the hydrocyclone sends smaller solids to underflow.

Narrow and accurate separation by density requires high centrifugal forces. The advantages of using a larger diameter cyclone are an increase in capacity and more tolerance of plate-like particles. The unfortunate tradeoff in using a larger hydrocyclone is that some separation accuracy of the products is sacrificed. As a larger diameter unit is used, the centrifugal force decreases and the separation cutpoint becomes less defined.

In selecting cyclones for experimentation in plastics recycling, 4-inch, 6-inch, and 10-inch diameter units were initially available. The 4-inch unit proved to be too small for practical use in most applications. Bridging of the apex orifice made investigation of this small unit impractical without extensive size reduction of the plastic particles. The 6 and 10-inch units proved worthy of further testing.

Inlet Orifice

The inlet orifice is the entrance point for the slurry. The size of this opening governs the velocity of the incoming fluid and the curvature of the inlet can prepare the fluid for “spiral” flow. By curving the inlet orifice, the fluid sees less turbulence on entry, which can produce a smaller overall pressure drop. Curved entries may also allow larger exit orifices to be used, which also reduces the amount of pressure drop within the unit. The larger orifice, in turn facilitates higher capacity, which is an important economic factor. The manufacturer generally fixes this parameter. Refer to Figure 3.

An involute entry pre-orients the particles prior to reaching the tangential point of contact with the cylinder wall. This minimizes turbulence and reduces the possibility of some particles being short-circuited into the vortex finder due to turbulence or ricochet action.[11] As noted earlier, excessive turbulence within a hydrocyclone can cause particles to report to the wrong discharge point, decreasing separation efficiency.

Vortex Finder

The vortex finder has a significant effect on the pressure drop across the cyclone as well as the cut point for the particles within the fluid. This is the discharge point for light and oversize (or platy) particles. Figure 1 depicts the extension of the vortex finder into the body of the hydrocyclone by a dotted line. Fundamentally, the vortex finder prevents particles from short-circuiting to the overflow. It forces all particles to travel below the fluid entry point so they are carried down into the body of the unit in the fluid flow. In effect, this gives them more time to respond as “light” or “heavy” in relation to the fluid density.

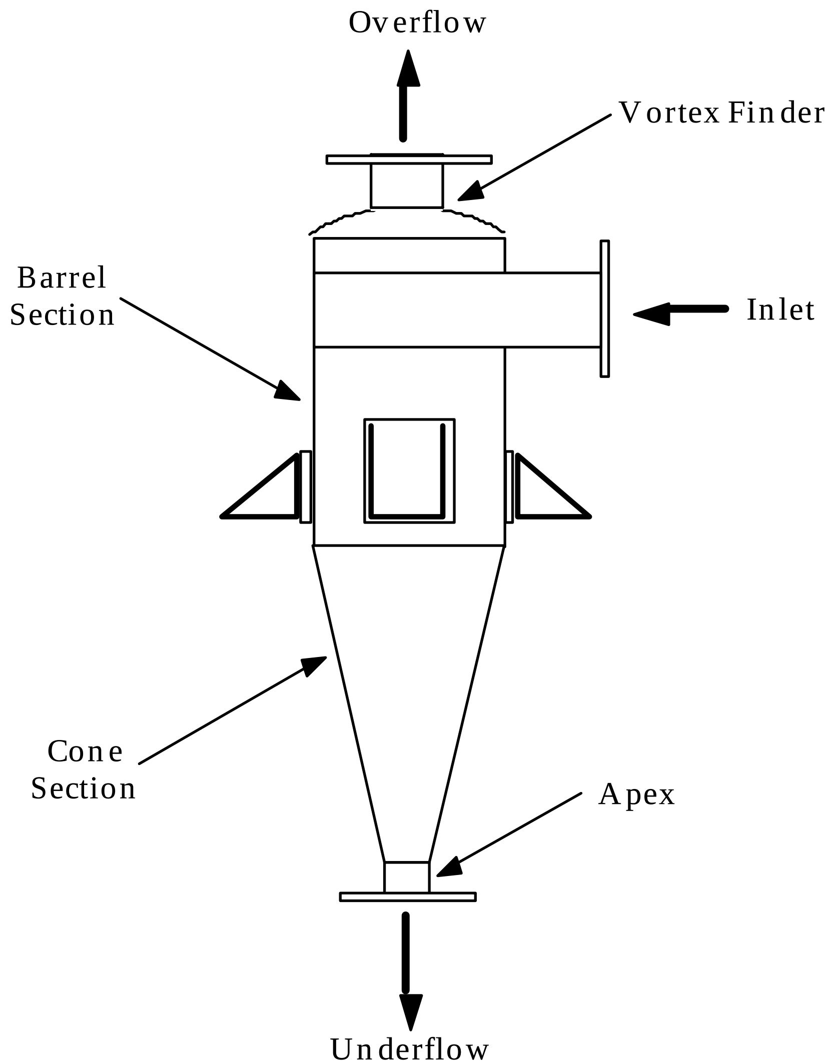


Figure 3. Hydrocyclone general arrangement.

There are two ways to adjust the vortex finder: length and diameter. Lengthening of the vortex finder below the inlet orifice forces the particles to remain in the cyclone longer and increases the efficiency of separation of light particles. Making the vortex finder too long can cause the heavy particles being carried down the wall of the barrel section to be entrained in the overflow. There is a careful optimum length that must be determined for best efficiency.

The diameter of the vortex finder has a significant effect on the separation point. A larger diameter causes more fluid to be carried to the overflow, thus lowering pressure drop and increasing capacity, however a point is reached when particles more dense than the media begin to be swept into the overflow stream. This diameter needs to be sized appropriately for the capacity of the system and for the desired cut point efficiency.

Apex

The function of the apex orifice is to discharge the heavy particles from the hydrocyclone. The diameter of this component is a key factor in determining the cut point for the cyclone. A larger diameter apex will increase fluid flow out through the underflow, carrying more particles to the heavies discharge. If the apex diameter is sized larger than the vortex, the cyclone will often drain itself through the apex and perform no separation. However, if the apex is sized too small, much of the heavies product may discharge with the lights.

Configurational Range Finding

Basic range-finding test work was required to determine how the operating variables effect the performance of the hydrocyclone. Specifically, a number of tests were performed on hydrocyclones to determine the parameters that effect the separation quality when separating two dissimilar plastics. The parameters investigated during these preliminary tests included: inlet flow, vortex diameter, apex diameter, vortex length, and overflow siphon.

Pump Characteristics

Because a high degree of flexibility in the feed flow was desired, it was necessary to investigate different methods of feeding at different flow volumes. It was also important to know the flow within the system quickly and accurately. MBA designed and built a test apparatus with variable speed drive on the inlet feed pump to allow for a flexible and finely tunable flow and a flow meter to display the pump's output.

Flow tests were performed to determine how pump capacity and flow would be effected by a variable speed system. Figures 4 and 5 show how flow and pressure were found to be essentially linear functions with regard to pump speed. Capacity and inlet pressure were directly related to pump speed through its normal operating range. This led to the understanding that hydrocyclone inlet pressure and pressure drop are important elements to designing a wet separation system using hydrocyclones. It was necessary to establish these relationships before undertaking further testing.

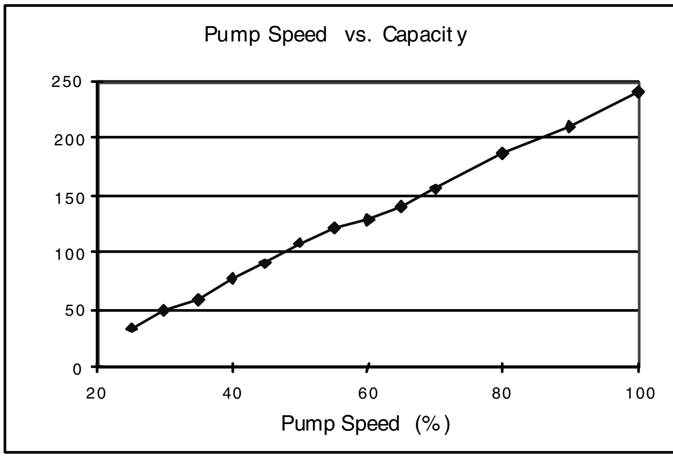


Figure 4. Pump speed vs. capacity.

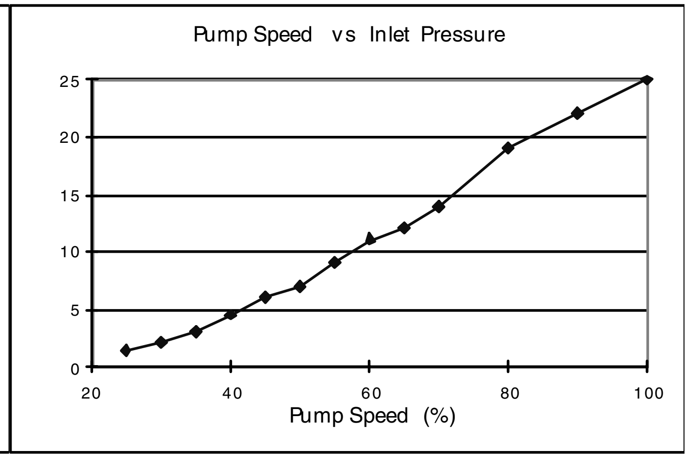
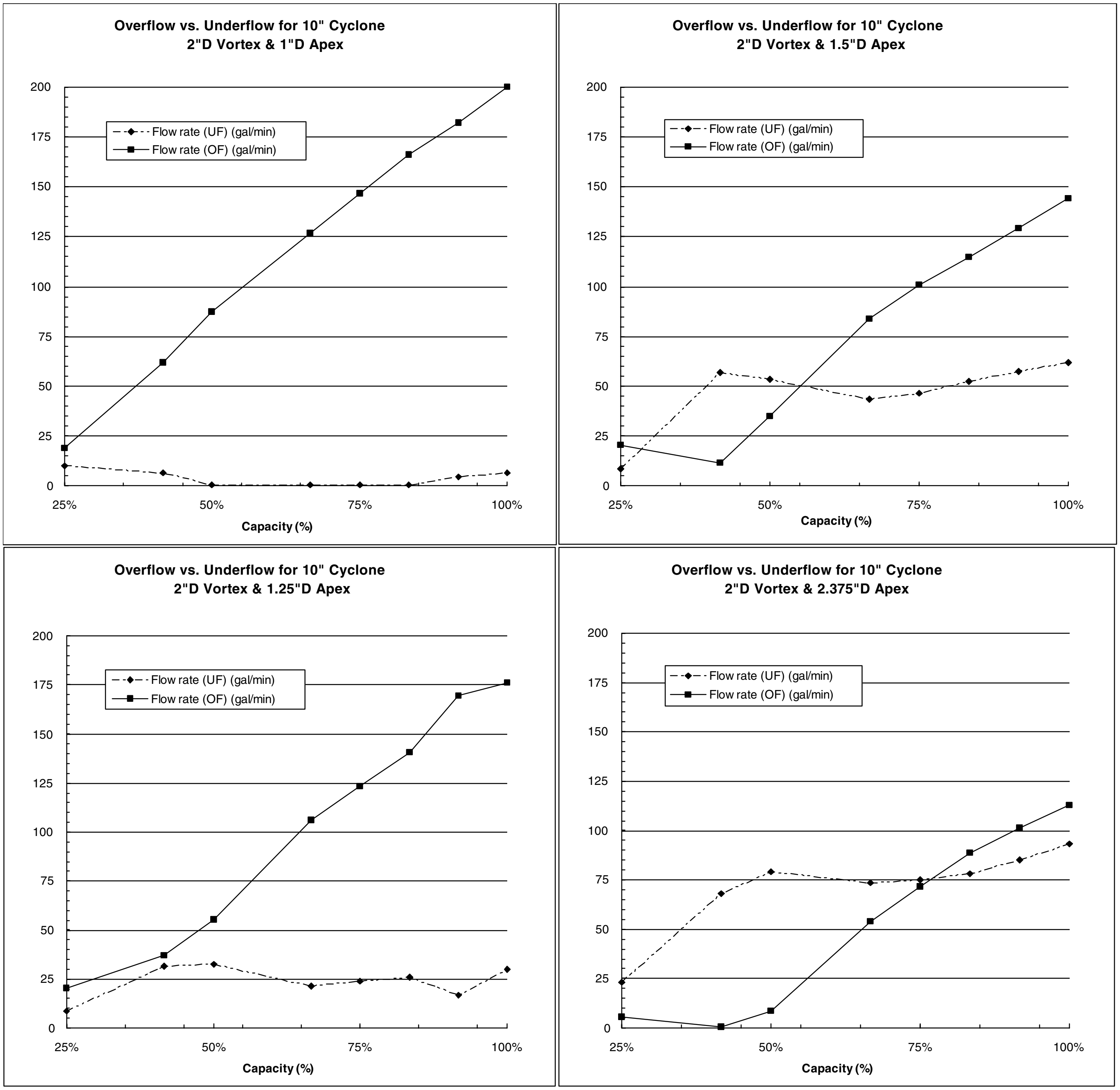


Figure 5. Pump speed vs. inlet pressure.

Hydrocyclone Flow Characteristics

The next series of tests were performed to determine the general flow characteristics of hydrocyclones. Specifically, tests were devised to determine how hydrocyclones would respond to inlet flow variations and how the overflow and underflow are interrelated. Flow split information is important in predicting how a cyclone will separate different materials from one another once they are introduced via the inlet. These tests were done using a 10-inch cyclone with an ambient pressure return drain to the feed tank. Figure 6 shows a family of curves that demonstrate the effect of increasing the apex diameter over a broad range of inlet flows for a given vortex finder size.

The cyclone was initially fitted with a 1-inch diameter apex and a 2-inch diameter vortex finder. In this test, there is virtually no flow discharging from the underflow, and nearly all flow is passing out the overflow. In a plastic separation application, this would send all solid material to the lights fraction. Increasing the apex to 1.25 inches (chart at bottom left) makes apex flow rise from zero to approximately 25 gpm (gallons per minute). While a 0.25" increase in diameter sounds small, it actually translates to almost a 60% increase in open area at the apex.



UF = Underflow, OF = Overflow

Figure 6. Hydrocyclone flow charts with increasing apex diameter.

In the third case (upper right), underflow actually rises above overflow for a period. This crossover point is important to note because it establishes an important operating range. The area to the left of the crossover creates very unstable flow patterns within the unit, and operating in this area would force light material to incorrectly report to the heavies port.

Finally, at 2 3/8 inches the underflow stays substantially higher than overflow throughout most of the flow range. This is a very unstable condition for a hydrocyclone since most of the fluid is simply draining out the bottom of the unit. However, operating to the right of this point, well above the unstable area, can produce flow conditions that are effective for plastic separations. By increasing the underflow volume, "heavy" materials are more likely to report properly to the underflow.

It is clear that the flow rate difference between overflow and underflow decreases as the apex approaches the vortex size. This makes sense because a larger apex will pass a greater amount of fluid, drawing more and more from the overflow, giving a more balanced flow in the cyclone. Unlike many other industrial uses of cyclones, plastic separation requires a more balanced flow to effect fine separation cut points. Conventional cyclones often have a flow split of 70/30 overflow to underflow. By experimenting with various combinations we found that this is not the ideal flow split to use when separating most durable plastics. It is better to allow more water to underflow than most conventional systems would dictate.

Vortex Finder Length

The third operating regime from the study just discussed was examined in more detail because it appeared to be the most promising. Experiments were undertaken to determine the effect of increasing vortex finder length and its interrelation with the apex. Figure 7 shows an example of the effect of vortex finder length changes to the flow characteristics. At low flow rates, the difference between the underflow and overflow becomes greater as the vortex finder length is increased from 12 inches to 19 inches in a 10-inch cyclone. Note that the overflow is substantially less than the underflow in both graphs below the crossover point, and with the longer vortex the crossover migrates to the right. Operating hydrocyclones in the area to the left is not recommended because it induces unstable flow conditions that are not ideal for separation work. The area to the right of the crossover is very similar in both cases.

This test did illuminate how the crossover tends to migrate with different vortex finders and which operating areas to avoid, but changing the vortex finder length over this rather wide range proved to not have a profound effect on the flow split. This allowed the elimination of vortex finder length as a significant variable in future flow testing.

Vortex finder length was standardized for each different sized cyclone to reduce operational variations. The diameter of the vortex opening was found to have a more profound effect on flow splits. Vortex finder length should not be completely discounted, however, because it does effect separation cut point.

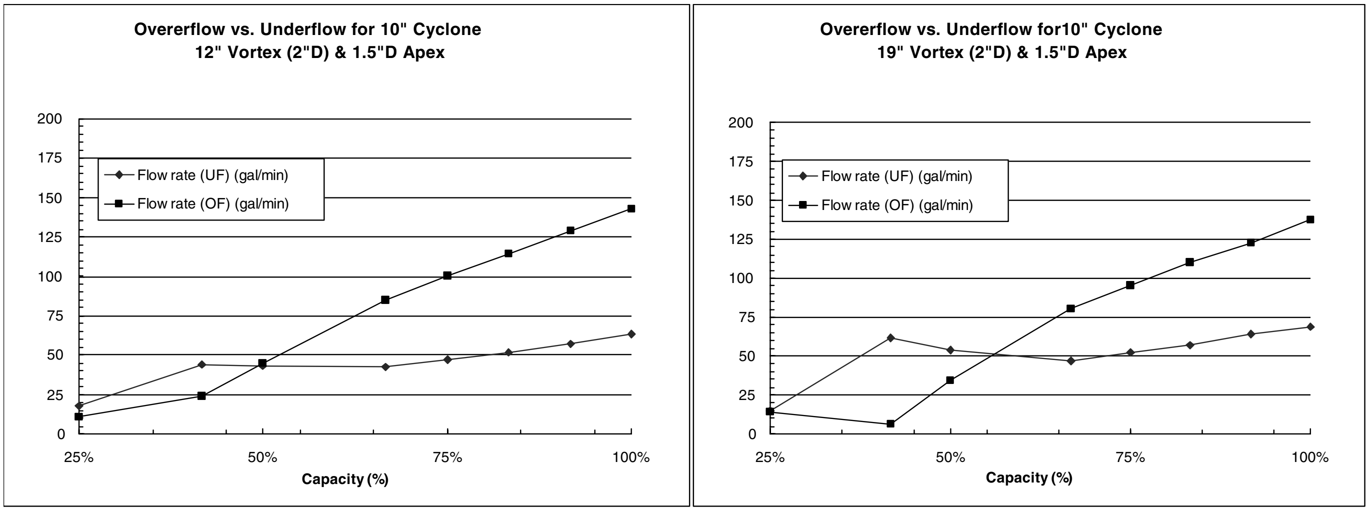


Figure 7. Hydrocyclone flow charts with increasing vortex finder length.

Siphons

The next area of testing investigated the effect of allowing a siphon to form on the overflow line. A siphon on the overflow of a hydrocyclone vacuum-draws fluid from within the unit out the overflow port. This can be used on either exit port to vary the amount of fluid through the port, thereby changing the split performed by the hydrocyclone. This is accomplished by not venting the port to be siphoned. Figure 8 shows a standard hydrocyclone discharge arrangement with the overflow to ambient pressure. This data is plotted as pressure vs. flow rate. At most of the lower part of the curve, the underflow (UF) gpm is higher than the corresponding overflow (OF) gpm. At approximately 55 percent of maximum pressure, the overflow volume becomes greater. In contrast, Figure 9 shows that with a siphon on the overflow connection, a more linear plot is generated for both OF and UF, and that the UF flow rate is always less than that of the OF. This is useful if one needs to operate cyclones in a wide pressure band and maintain a fairly uniform flow split, or if it is necessary to pull some product that would normally report to the underflow into the overflow stream. The overflow and underflow can similarly be balanced by tilting the cyclone so that there is less of a height difference between the overflow and the underflow. Tilting a cyclone toward the horizontal allows more water to report to the overflow. Installing cyclones in a tilted configuration, however, can complicate piping arrangements and make the unit difficult to drain after use.

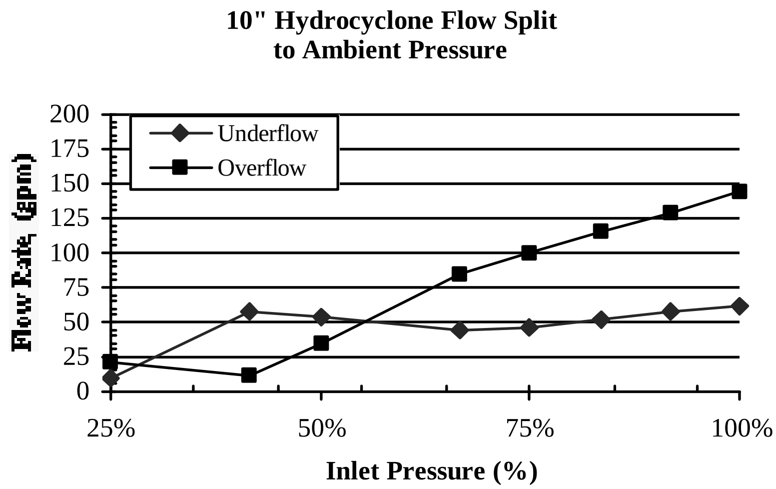


Figure 8. Flow Split with Overflow to Ambient Pressure.

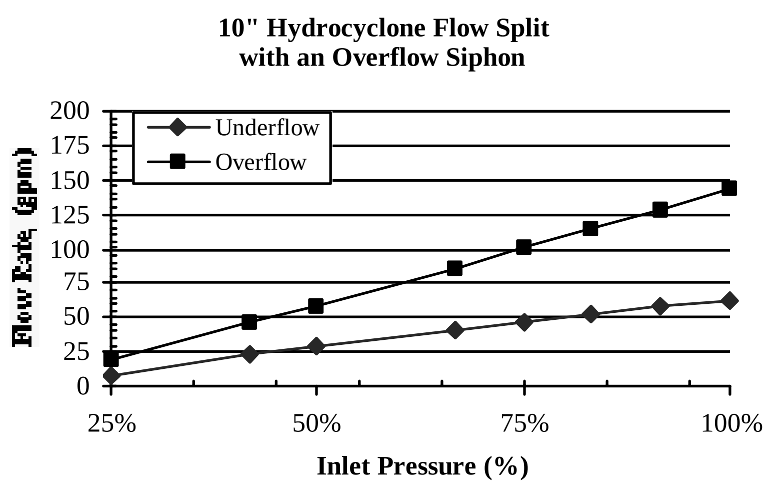


Figure 9. Flow Split with Overflow Siphon.

Range finding trials utilizing various operating parameters confirmed that hydrocyclone separation performance is very sensitive to a number of variables. The range finding also helped determine the reasonable ranges for more detailed investigations. Due to the complexity and time-intensive nature of these tests, and the potential for interaction among these variables, an Experimental Design approach was ultimately employed to more accurately determine efficient separation design parameters (see later section). Before undertaking this advanced experimental approach, however, additional preliminary experiments to understand the basic behavior of hydrocyclones operating under different conditions was necessary. These experiments proved to be very valuable in determining potential operating ranges for additional studies.

Configuration of Hydrocyclones

A series of tests were performed to generate partition curves for a range of materials. This shows which cyclone combination is best suited for separating particles of a given dimension and the accuracy with which a cyclone can make a separation.

To perform these studies it is first necessary to obtain a series of samples within a very tight density range (0.002 g/cc). In this case, the samples were color coded to facilitate the analysis of the results from each separation test. It is necessary to have an extremely narrow density band for each material to improve experimental precision during separations testing. Water was chosen as the media to demonstrate the system's effectiveness at low density, to remove any possible uncertainties due to density modifier aberrations, and for ease of testing.

The materials chosen were a series of polypropylene plaques with different filler contents ranging from unfilled to 40% talc filled. Montell North America, Inc. kindly compounded and molded five different colored samples of polypropylene with 0%, 10%, 20%, 30%, and 40% talc filler thereby providing a range of material densities between 0.895 and 1.118 g/cc for the tests. Laboratory sizing and separation was performed on these samples to determine their density range within 0.002 g/cc. These samples were cut in 1/8" cubes and then oven heated to slightly round any sharp corners. Then a precisely monitored sink-float salt solution was used to accurately determine the density of the test samples. Figure 10 shows the density distributions of two of the colored samples used for blending.

Because the Montell polypropylene plaques received could not provide a sufficiently narrow density distribution around 1.000, it was necessary to blend new samples at MBA's lab. Two differently filled polypropylene samples were blended to achieve a closer density bracket around the 1.000, which is approximately the density of pure water. By blending various colored samples together, a precise density could be targeted to yield sample chips within a specific range. The two samples shown in Figure 10 represent the two closest plaques to 1.000 specific gravity. Figure 11 shows the result of blending these white and blue plaques. Other plaques were similarly blended to yield a wider variety of plaques.

These plaques were then precisely sized to achieve an exact particle shape. Since shape is a pivotal variable in hydrocyclone use, cube-shaped samples for each density point were generated. These cube-shaped particles closely approximated the performance of ideal particles in a water stream. This step was taken to reduce potentially misleading data due to particle shape factors as discussed earlier. Finally, the cube-shaped particles were density separated to yield a close-tolerance array of samples shown in Table 1.

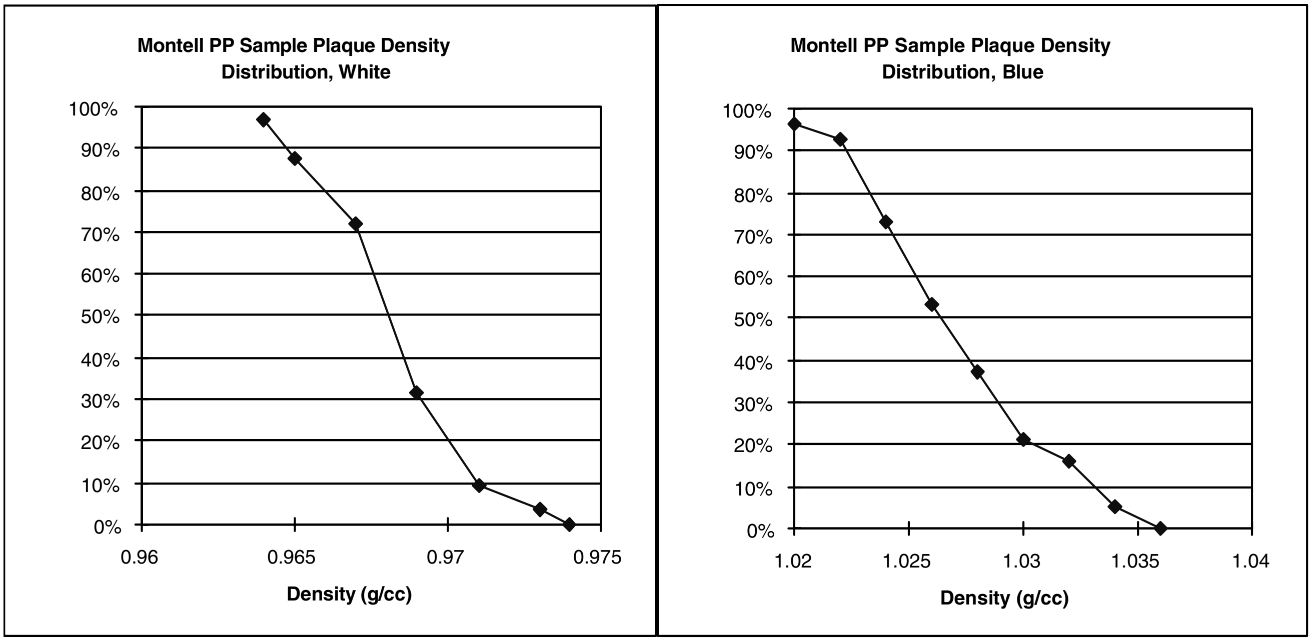


Figure 10. Density distribution graphs for two Montell polypropylene sample plaques.

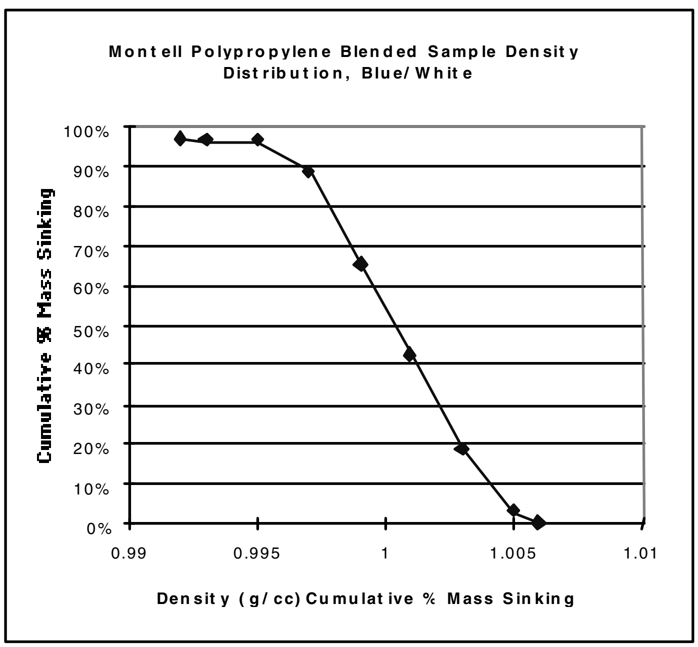


Figure 11. Density distribution for a blended polypropylene sample plaque.

Table 1. Controlled sample chip densities.

Color	Density
Black/White	0.953
White	0.965
White/Gray	0.976
Gray/White	0.987
Blue/White	0.997
Gray/Black	1.005
Blue	1.026

This mixture of samples was run in both the 6 and 10-inch hydrocyclones to determine proper cyclone configuration (i.e. vortex and apex combination). Then, the best performing configuration was run at a number of different operating conditions to determine the best conditions for this separation. This provided a means of modeling how each cyclone performed at those test conditions, and this model yielded a partition curve for each cyclone at the given test configuration.

The slope of the partition curve reveals how tightly each combination is capable of separating materials with closely bunched densities. A nearly vertical curve means an excellent separation was achieved. Partition curves thus provide a quantitative means of comparing various cyclone combinations, and are a tool to determine how tightly hydrocyclones can reliably make density separations.

From an experimental standpoint, this data clearly demonstrates the challenges with obtaining samples with precise densities, which is an absolute requirement for this type of evaluation. Perhaps even more importantly, these results illustrate one of the challenges associated with density-based separations. Material densities can vary from lot to lot due to slight compositional changes, from part to part due to processing changes, and even between different sections within the same part, especially when multiple cross-sectional thicknesses are present. The samples used in this test involve the best case because:

1) the material was compounded in a single small lot for this purpose,
2) the plaques were all molded on the same equipment under the same conditions, and
3) the plaques were of a uniform thickness so the potential for differential cooling rates was minimized.

Partition Curve Accuracy

It is important to have adequate data point coverage in the critical areas of a particular plot to ensure that partition curves accurately reflect the separation characteristics throughout the range of operation. Specifically, it is important to have sufficient data points to properly evaluate the slope of the curve from above its 95% point to below its 5% point when trying to determine the effective cut point for a given cyclone separation.

The first test shown in Figure 12 was performed without the 0.95 g/cc density data point. According to this graph, the 95% point coincides with a density of about 0.935. When the test was performed again using sample chips with a density of 0.951, it was discovered that all of these chips would report to overflow and therefore the 95% point actually coincides with a density of nearly 0.960. The error associated with using the first test to set-up the operating parameters for this type of separation could therefore be nearly 0.025 g/cc. This could potentially lead to contaminant plastics reporting erroneously to underflow or overflow.

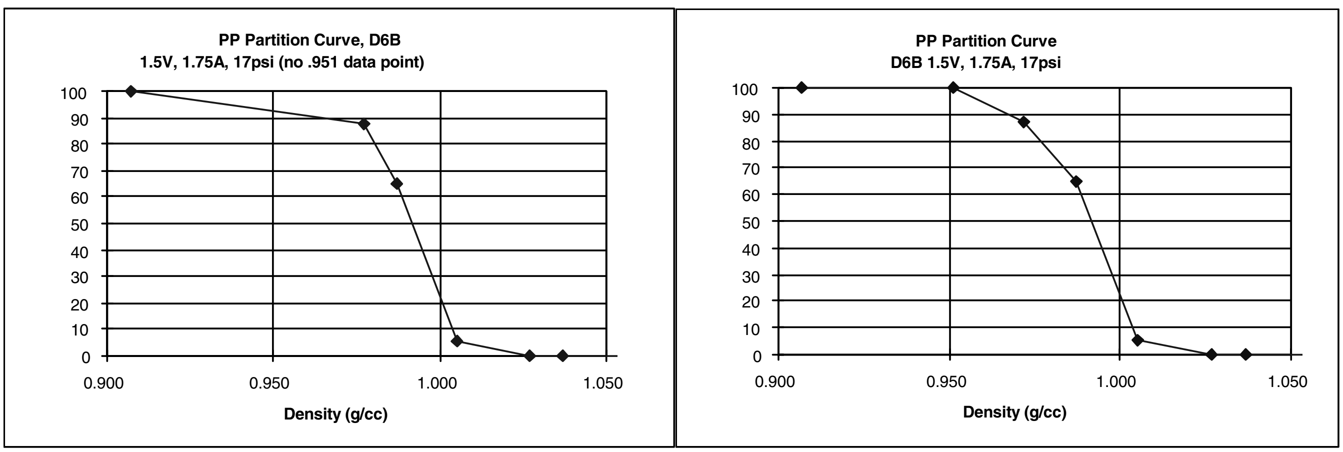


Figure 12. Partition curves with and without 0.951 data point for accuracy.

Pressure Change

Hydrocyclones must be fed under a certain amount of pressure in order to create the proper vortex conditions within the unit. Formation of an air core within a cyclone is an indication of vortex stability, and it is essential that the feed rate and pressure be sufficient to maintain this stability. For any cyclone there is a minimum flow rate and consequently a minimum pressure drop or feed pressure. Some observations of air core formation have indicated that the minimum pressure drop in normal designs is about 5 psi.[12]

An approximate guide to vortex stability can be given theoretically by calculating the conditions under which the rotational speed at the periphery gives a centrifugal acceleration that is less than gravitational acceleration. Conditions that generate acceleration in a radial direction of less than 1 x “g” will obviously be bordering on instability.[13] This minimum pressure condition is illustrated in Figure 13 for tests performed in the MBA laboratory. In the 25 psi and 17 psi tests, the cyclone is operating in a range that is producing a stable vortex. When the pressure is reduced to 10 psi, the vortex becomes unstable and the unit tends to drain most of the plastic chips to the underflow regardless of their density. For this particular arrangement, the minimum inlet pressure is above 10 psi.

Once the range of stable operation was established, it was necessary to evaluate the advantages of running either 17 psi or 25 psi. The top two lines in Figure 13 represent these two operating conditions. The two most important data points to consider are the 0.987, and 1.005 g/cc because this test was performed using tap water with a measured specific gravity of 0.998 as the media. The steep-ness of the slope between these two points, across the media density, will indicate the best pressure condition for this media and cyclone arrangement.

On the 17 psi graph, the line between these two points is quite steep, dropping from 65% down to 5%. Increasing the pressure to 25 psi tends to draw 0.987 density chips, which should report to overflow, to exit with the heavies. It also causes more than 20% of 1.005 g/cc material to report incorrectly to overflow. However, this curve is steep between the 0.976 point and the .987 point, giving the effect of lowering the media density. In general, this increase in pressure drives the most effective separation point to the left, artificially lowering the media density.

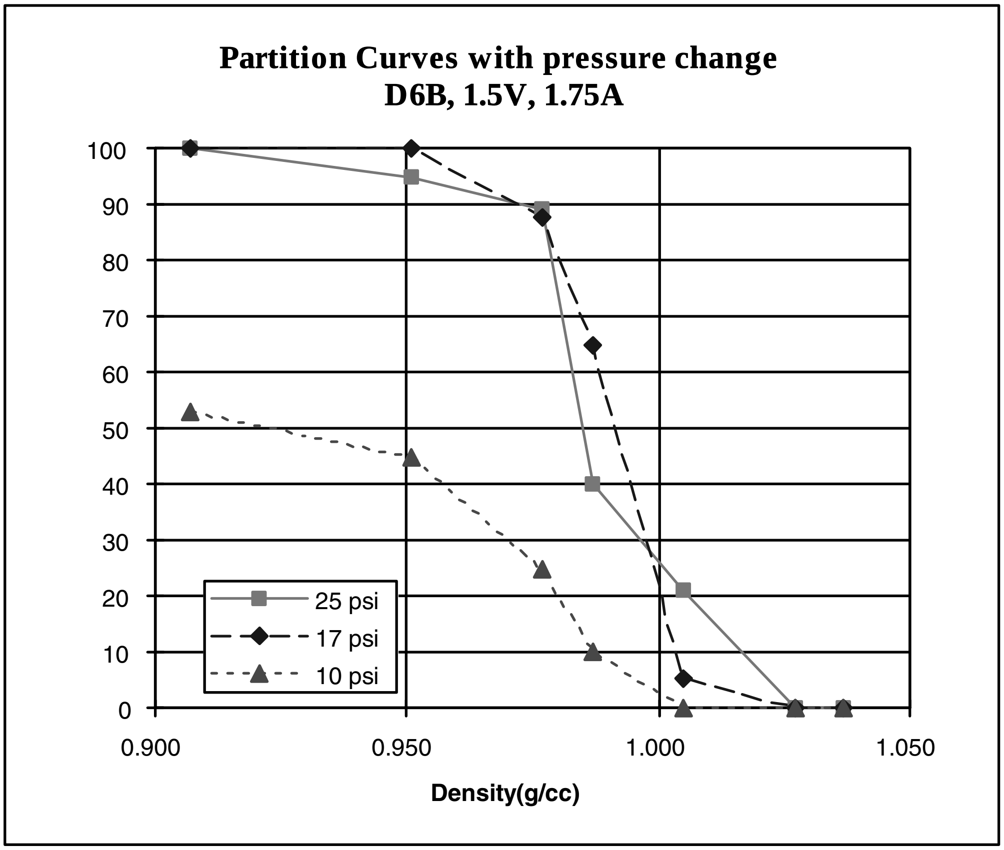


Figure 13. Effect of decreasing feed pressure in a hydrocyclone.

Changing Vortex Finder Diameter

Conventional hydrocyclones often have a flow split in the range of 70/30 overflow to underflow. By experimenting with various combinations we found that this is not necessarily the ideal flow split to use when separating most durable plastics. It is usually better to allow more fluid to the underflow than most conventional systems would dictate.

Increasing the vortex finder diameter of a hydrocyclone tends to drive more fluid and material to the overflow, all other conditions being equal. A test was performed to illustrate how much of an effect increasing the vortex a relatively small amount, 1/4”, would have on the partition curve. (In this case the change of 0.125" represents a 37% increase in area.) By increasing the vortex 1/4” in this test, the overflow cut point efficiency was increased by 5 to 10% over the span of the curve. It also appears that the light materials are responding more precisely to the larger vortex, since material below the 0.972 point with the smaller vortex hover at the 90% point while the experiment using the 1.75” vortex resulted in 100% of these particles correctly reporting to the overflow.

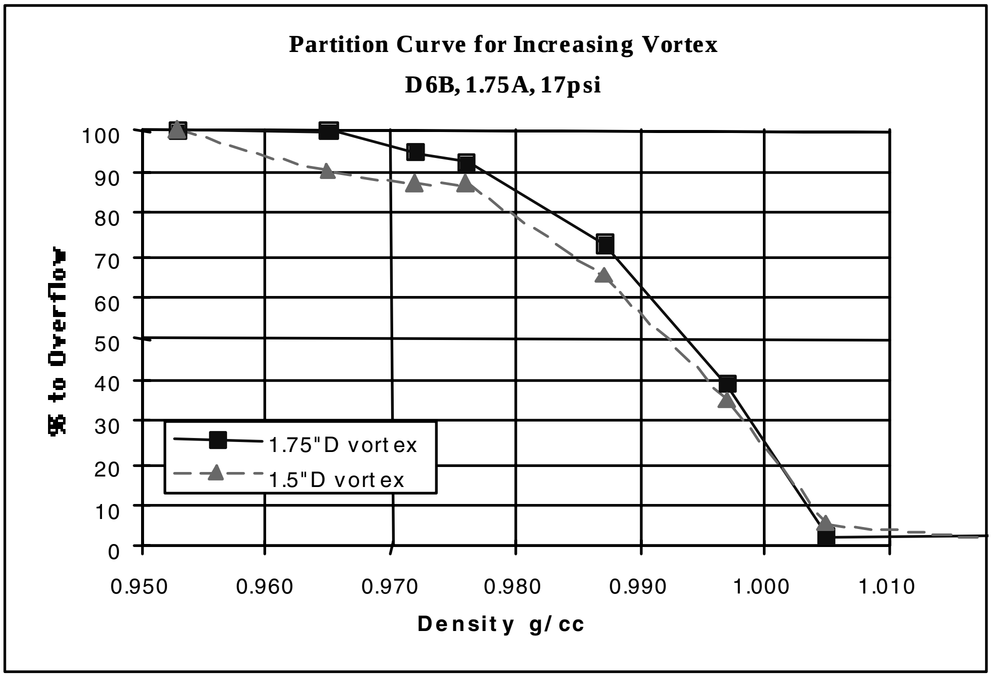


Figure 14. Effect of changing vortex diameter on a hydrocyclone.

There are at least two complex aspects to hydrocyclone performance that are influenced by vortex finder diameter: short circuit flow across the roof and down the outside wall of the vortex finder, and the position of the locus of zero vertical velocity within the cyclone. Short circuit flow tends to draw materials from the fluid inlet port and directly to the overflow discharge without actually spiraling within the cyclone, thus eliminating the opportunity for accurate separation.

The locus of zero vertical velocity is a conical surface within the hydrocyclone at which there is no upward or downward velocity. Its shape is similar to that of the hydrocyclone. All particles pass through this locus, or cone, on their way to deciding if they should report to the overflow or underflow. If particles are allowed to avoid this “decision zone”, they may report incorrectly. The outside diameter of the vortex finder is important here because it determines where the feed material will see the locus of zero vertical velocity.

It appears to be undesirable to have the overflow diameter greater than the base diameter of the locus of zero vertical velocity. This causes collapse of the normal patterns of inward radial flow. Inward radial flow occurs over the entire length of the cyclone body with consequent opportunity for the carrying of particles to the overflow stream before they have had an opportunity to attain their equilibrium orbit positions.[14] An in-depth analysis of these parameters is beyond the scope of this paper. This explanation was simply meant to advise the reader of some of the complex flow patterns that occur in hydrocyclones and how changing various factors such as vortex finder diameter can influence them, sometimes in unpredictable ways.

Changing Apex Diameter

Increasing the apex diameter tends to draw more fluid and plastic material to the underflow. A test was performed to evaluate the effect of increasing the apex by 1/4". Figure 15 shows that as the apex diameter is increased, the graph shifts down and to the left by nearly 20%. This rather small increase in diameter has a large effect on the separation. The larger apex ensures that all the particles at 1.005 specific gravity report to the underflow, however it reduces the efficiency of the cyclone in separating light materials. The smaller apex, under these conditions, is more efficient at separating the materials across the 1.000 density. It has a drop of 50% from 0.995 to 1.005. The larger apex only drops about 40%.

A larger apex will, in general, polish the overflow because it will tend to draw any materials of a suspect density to the underflow, keeping the overflow clean of potential impurities.

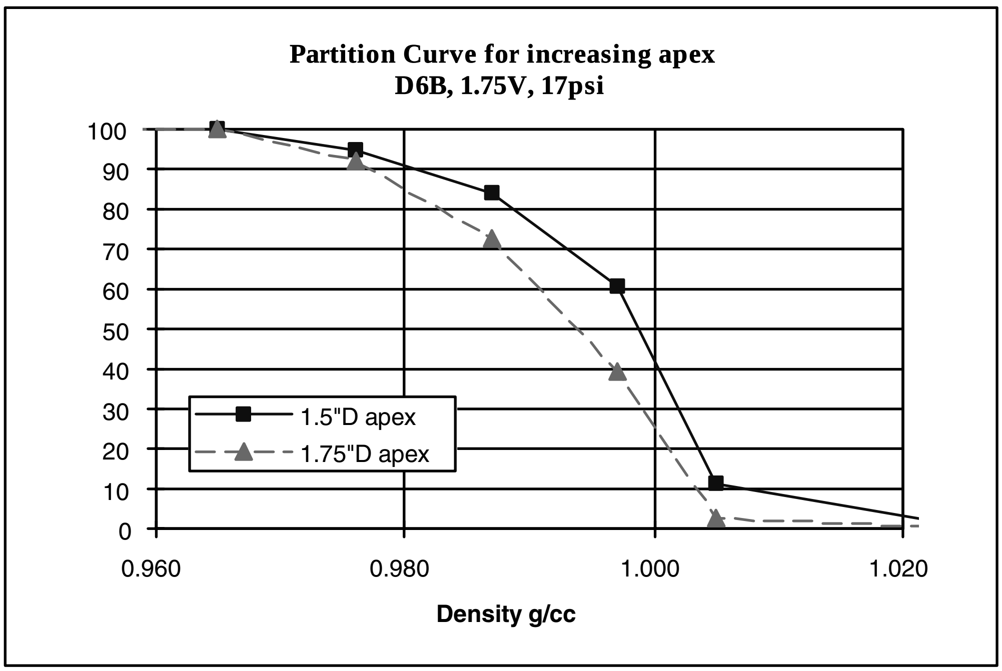


Figure 15. Effect of changing apex diameter on a hydrocyclone.

Experimental Design

Background

The process of determining the initial operating conditions for the various hydrocyclones involved a good deal of "educated trial and error". This is quite acceptable for simple processes or for range-finding and basic characterization studies.

The information generated from this type of experimentation is also useful if the process being studied is expected to change little and the materials to be separated are rather uniform and consistent. This is the case with many manufacturing and material processing operations. Any process to recover plastics from durable goods, however, must be prepared to handle materials with widely varying densities and particle shape/thickness from batch to batch. Therefore the process must be understood in a broader sense and it is desirable to have some predictive capabilities. One would like to predict the ideal configuration of the process for a wide range of materials.

Experimental design techniques have been successfully used in a wide range of industries to understand complex operations and to model the performance of those operations for process control and optimization. For this reason it was decided to adopt this approach for the next phase of hydrocyclone studies.

A series of experimental designs were undertaken to first determine the optimum conditions under which to run a hydrocyclone to effect the best and most efficient separation of plastic particles. To our knowledge this was the first time this has been done. The method chosen was a Box-Behnken (B-B) experimental design using thirteen different experimental points in a three variable model to predict trends in the system. The three variables used were Vortex Diameter, Apex Diameter, and Inlet Pressure. This points to another significant advantage of experimental design approaches: a reduction in the number of tests required to evaluate a given range of variables. This is possible because the approach employs statistical modeling techniques. The modeling also provides the ability to predict trends that may be outside of the test boundaries. If all possible combinations of the three variables at three different axes were used, 27 points would be required, assuming all endpoints and midpoints were tested. Only 15 test points are required with the B-B design, twelve boundary points and the center point conditions, which are replicated three times to determine test reproducibility.

The B-B design does not contain any corner points in the design space. Therefore, it is also an attractive option for experiments where corner points are infeasible due to operating limitations. If only 3 factors were used, the design would appear graphically as shown in Figure 16. The B-B designs allow for estimating main effects, quadratic effects, and all linear two-way interactions.[15] A detailed description of this advanced statistical modeling approach is beyond the scope of this paper, and the reader is referred to the references cited for additional information.

Experimental

The first designed experiment was performed on a six-inch diameter hydrocyclone. Information from the earlier range-finding experiments was used to suggest reasonable ranges for each of three variables. After the first set of experiments was completed, the subsequent analysis of the data suggested that the optimum operating parameters were near an edge of the chosen variable range, so a second iteration was undertaken.

For the next designed experiment, the variables were changed slightly to concentrate on the most promising areas. The variables used for the first and second models are displayed graphically in Figure 17. Table 2 lists the actual combination of various conditions used for the two sets of experiments.

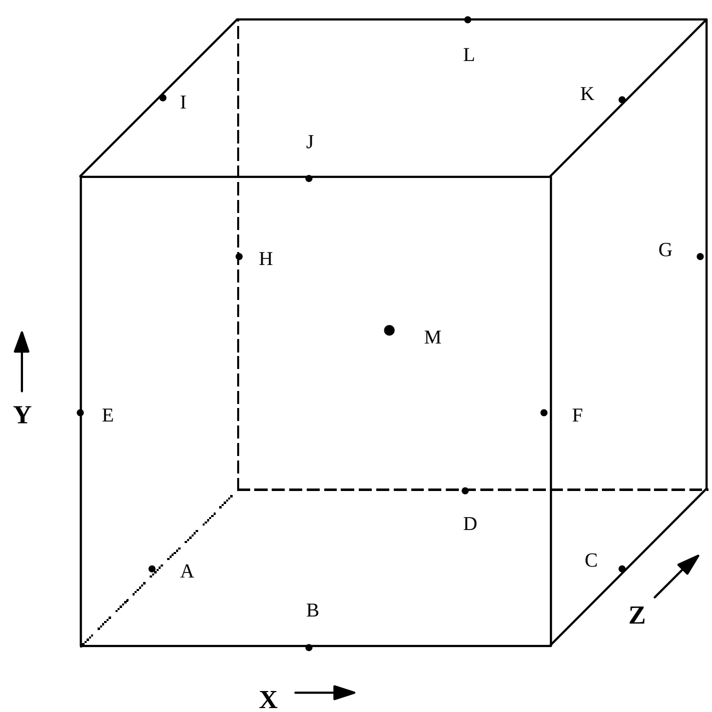


Figure 16. Geometric representation of Box-Behnken design for 3 factors**.**
Samples of ABS and PP were used to assess the effectiveness of each trial separation. Vortex diameter, apex diameter, and pressure were adjusted according to the schedule given in Table 2. In a perfect separation, all of the PP should report to the overflow and all of the ABS to the

underflow. The relative effectiveness of each test point was gauged by the percent of ABS to the underflow stream.

The results from the first series of experiments are summarized in Table 3. It can be seen from this Table that the best results were obtained during experiment C with a 1.75 inch Apex Diameter and a 1.5 inch Vortex Diameter at 10 psi. These conditions yielded a 100% PP overflow and 98% ABS underflow in a single pass. Based on this success, a second series was run to concentrate on this area. As these conditions were at one edge of the experimental space, it was decided to undertake a second experimental design more centered around these conditions (see again, Figure 17).

The second series of experiments were very successful. The results from the Box-Behnken experimental design were then used in conjunction with a computer-modeling program to create a statistical model (Figure 18). The model was then used to generate a contour plot showing how the performance of the hydrocyclone changes at different apex and vortex combinations at 10 psi (Figure 19).

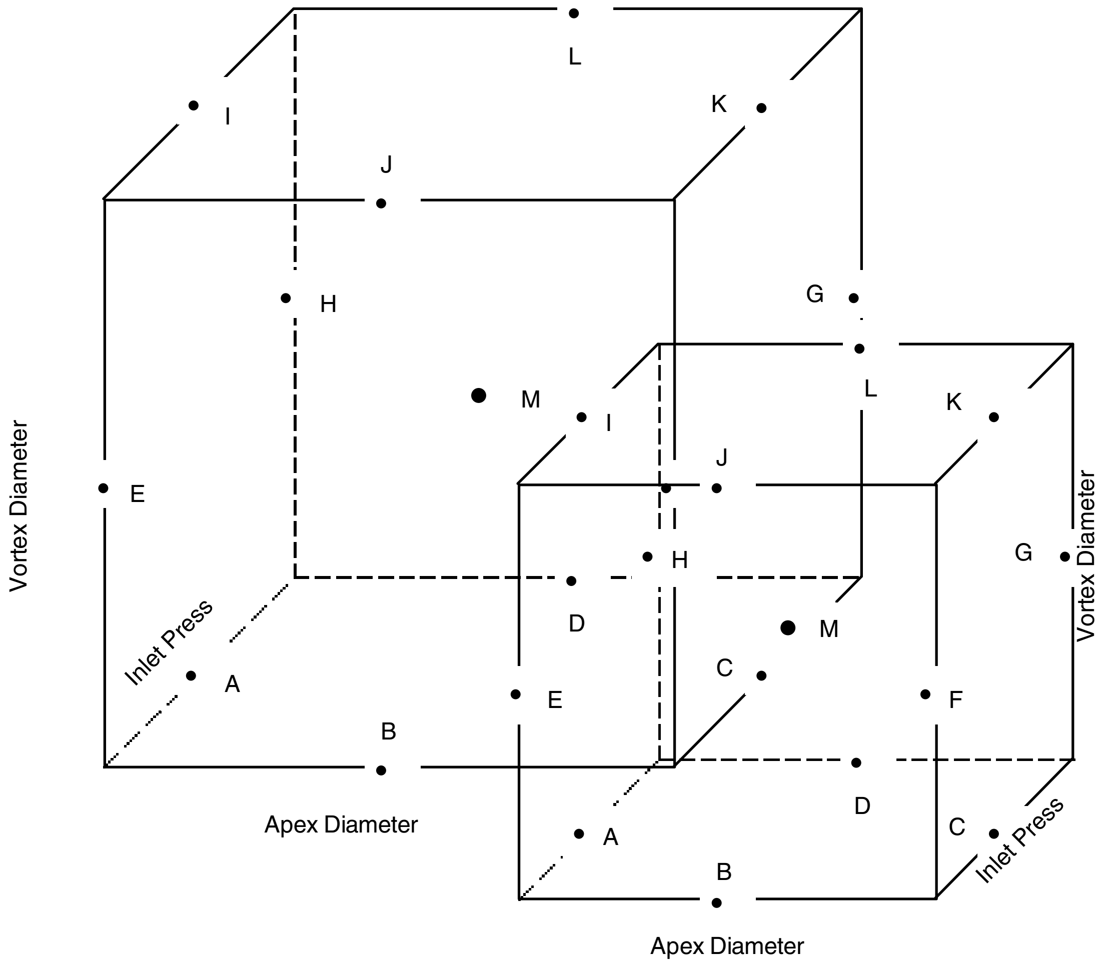


Figure 17. Box-Behnken experimental schematic for D6B configuration optimization.

Table 2. Variables for experimental designs on a D6B hydrocyclone.

	Apex Diameter (in)		**Vortex Finder Diameter (in)**		**Inlet Pressure (psi)**	
Trial	**1**	**2**	**1**	**2**	**1**	**2**
A	.625	1.5	1.5	1	10	12
B	1	1.75	1.5	1	4	7
C	1.75	2	1.5	1	10	12
D	1	1.75	1.5	1	20	25
E	.625	1.5	2.25	1.75	4	7
F	1.75	2	2.25	1.75	4	7
G	1.75	2	2.25	1.75	20	25
H	.625	1.5	2.25	1.75	20	25
I	.625	1.5	3	2	10	12
J	1	1.75	3	2	4	7
K	1.75	2	3	2	10	12
L	1	1.75	3	2	20	25
M	1	1.75	2.25	1.75	10	12

Table 3. Yield for D6B hydrocyclone test #1 using PP and ABS.

	Apex Dia. (in.)	Vortex Dia. (in.)	Inlet Press. (psi)	Wt. % PP Overflow	Wt.% PP Underflow	Wt. % ABS Overflow	Wt.% ABS Underflow
A	0.625	1.50	10	100%	0%	82%	18%
B	1.000	1.50	4	100%	0%	41%	59%
C	1.750	1.50	10	100%	0%	2%	98%
D	1.000	1.50	20	100%	0%	48%	52%
E	0.625	2.25	4	100%	0%	81%	19%
F	1.750	2.25	4	76%	24%	6%	94%
G	1.750	2.25	20	100%	0%	13%	87%
H	0.625	2.25	20	100%	0%	87%	13%
I	0.625	3.00	10	90%	10%	42%	58%
J	1.000	3.00	4	93%	7%	28%	72%
K	1.750	3.00	10	93%	7%	15%	85%
L	1.000	3.00	20	49%	51%	29%	71%
M	1.000	2.25	10	100%	0%	43%	57%
M	1.000	2.25	10	100%	0%	38%	62%
M	1.000	2.25	10	100%	0%	39%	61%

Table 4. Yield for D6B hydrocyclone test #2 using PP and ABS.

	Apex Dia. (in.)	Vortex Dia. (in.)	Inlet Press. (psi)	Wt. % PP Overflow	Wt.% PP Underflow	Wt. % ABS Overflow	Wt.% ABS Underflow
A	1.50	1.00	12	7%	93%	0%	100%
B	1.75	1.00	7	0%	100%	0%	100%
C	2.00	1.00	12	0%	100%	0%	100%
D	1.75	1.00	25	0%	100%	0%	100%
E	1.50	1.75	7	100%	0%	14%	86%
F	2.00	1.75	7	6%	94%	0.5%	100%
G	2.00	1.75	25	97%	3%	3%	97%
H	1.50	1.75	25	100%	0%	17%	83%
I	1.50	2.00	12	100%	0%	15%	85%
J	1.75	2.00	7	100%	0%	12%	88%
K	2.00	2.00	12	100%	0%	5%	95%
L	1.75	2.00	25	100%	0%	11%	89%
M	1.75	1.75	12	100%	0%	8%	92%
M	1.75	1.75	12	100%	0%	8%	92%
M	1.75	1.75	12	100%	0%	6%	94%

Response: ABS Underflow

Summary of Fit

RSquare	0.960769
RSquare Adj	0.943332
Root Mean Square Error	6.547019
Mean of Response	59.64286
Observations (or Sum Wgts)	14

Whole-Model Test

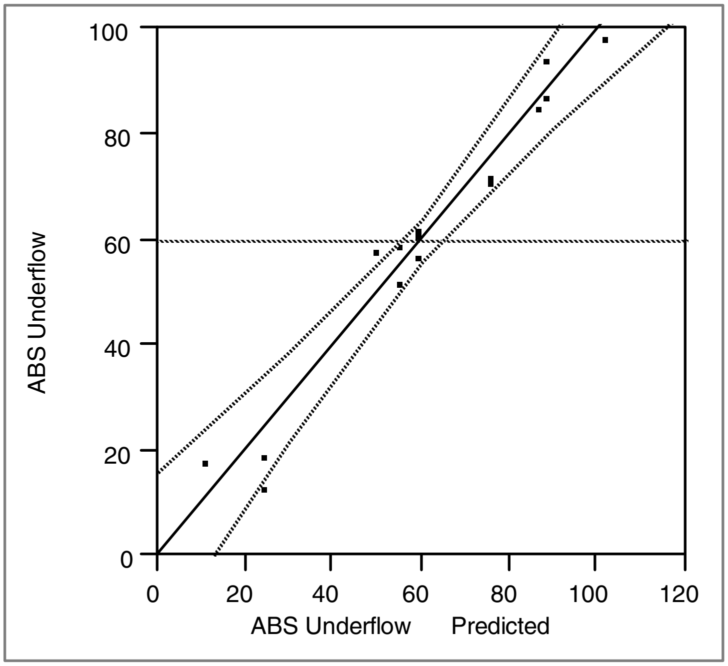


Figure 18. Statistical modeling data for 6 inch hydrocyclone.

This analysis generates a great deal of information. (Please note that the data shown is for the ABS underflow stream only.) While a detailed description of all of the statistical data is beyond the scope of this paper, the most important parts of this analysis will be briefly introduced.

Contour Plot

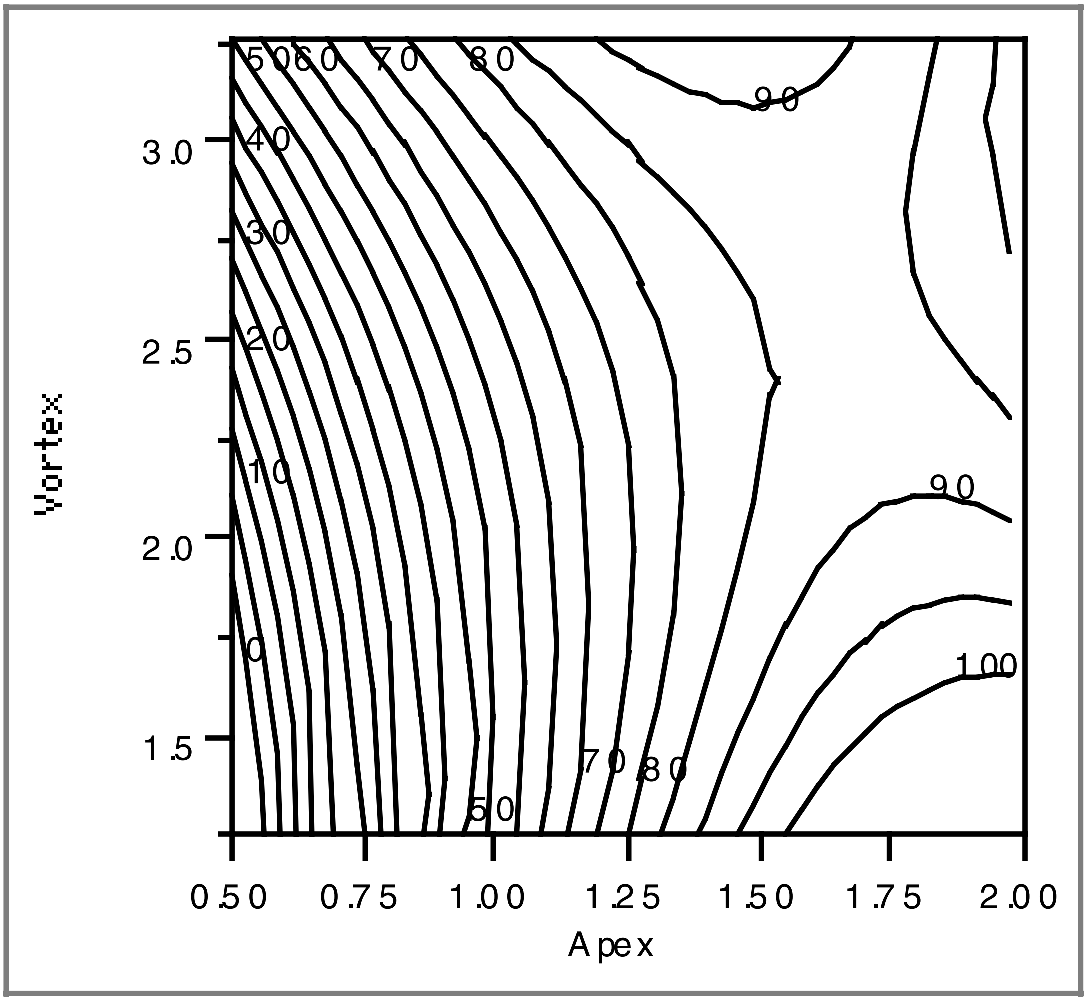


Figure 19. Contour plot for Box-Behnken experimental design.

For the purpose of process modeling, the most pertinent measures of model accuracy are the R-squared value, the R-squared adjust, the whole-model test graph, and the contour plot. The R-squared value of 0.96 (96%) indicates that the model fits the data rather well and is successful at predicting its trends; the R-squared Adjust value factors in the number of variables used and is also rather high at 0.94 (94%). The whole-model test graph illustrates how the data falls nicely within the 95% error curves, which sandwich the line of perfect fit. The dashed line running horizontally at 60% is the mean value line. It is important that this line only briefly crosses the model fit area, because the model prediction should be quite different from this simple "averaging" of the data (otherwise there would be no need for a model).

Lastly the contour plot graphically indicates that the area of best separation is just what the data in Tables 3 and 4 show to be true: 95-100% separation effectiveness at Apex=1.75, and Vortex=1.5.

The contour plot may be interpreted in the same manner as a topographical map. The numbers written on the curves represent the percent of ABS to underflow, the higher the better. The left-hand section of the graph is a steeply sloped section, increasing in separation accuracy as the apex diameter increases. There is a saddle point at about 90%, which corresponds to an apex of 1.75" and a vortex of 2.5". The graph ultimately increases to 100% in the lower right-hand portion. This is the area of optimal cyclone performance given this cyclone type and size, its arrangement, and the desired material split. Plots like these can be used to visualize and predict how a system's performance will change with different operating parameters.

Summary

Hydrocyclones are inherently complicated pieces of equipment to operate. Their performance is effected by a number of different parameters, and understanding these parameters is both important and difficult. However, once they are mastered, hydrocyclones can become a cost-effective and space-saving method for plastics' separation.

Hydrocyclones can clearly be used to separate plastics or other materials having different densities using a free flowing media like water. The most important operating parameters for plastic separation use appear to be vortex diameter and apex diameter. A minimum pressure must be reached for vortex stability, but beyond that, the effects of pressure on hydrocyclone performance do not appear to be as significant as those associated to changes in the vortex and apex diameters.

It is very important to determine first the general operating characteristics of the hydrocyclone and pump arrangement to ensure that they can be operated in a stable regime. The general effects of changes to the important operating parameters can then be investigated. Finally, experimental design methods can be used to optimize and model the performance for specific material streams. These models can be used, in turn, to suggest the initial operating ranges for different streams.

Endnotes

[1] These figures are merely estimates based on information obtained from manufacturers of this equipment and experience gained by MBA Polymers, Inc. in specifying such equipment.

[2] It should be noted that Humboldt Decanter believes that its Censor® centrifuge system has lower processing costs than sink-float systems for a variety of reasons, particularly for hard to handle materials such as films and fibers. See product literature from the company and "Recycling and Recovery of Plastics", Brandrup, J.; Bittner, M.; Michaeli, W.; and Menges, G., Hanser Publishers, Munich, 1995, p. 260-263.

[3] Svarovsky, L. Hydrocyclones. Technomic Publishing Co, Lancaster, PA, 1984. p. 165.

[4] German Patent Number 39,219 and US Patent Number 325,521.

[5] US Patent Number 453,105.

[6] Bradley, D. The Hydrocyclone, p.5.

[7] Bradley, D. The Hydrocyclone, p.6.

[8] Bradley, D. The Hydrocyclone. Pergamon Press, New York, 1965. p. 2.

[9] Bradley, D. The hydrocyclone p.2

[10] Bradley, D. The Hydrocyclone p.139.

[11] Krebs Engineers. Krebs Installation-Operation-Maintenance Manual. Menlo Park, CA.

[12] Bradley, D. The Hydrocyclone. p.11.

[13] Bradley, D. The Hydrocyclone. p.11.

[14] Bradley, D. The Hydrocyclone. p.111

[15] Schmidt, Launsby. Understanding Industrial Design Experiments. p. 3-24.