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Dynamic Imaging Enables Factory 4.0 in Sugar Production

Abstract

Dynamic imaging is now a standard item in the design of sugar factories. Over the past 35 years we have seen the reliable installations of imaging systems prove a significant payback and reduce labor costs while improving quality and production throughput. The applications include level and cake measurement to reduce wash water in batch centrifuges, color line control in continuous centrifuges, seeding control in batch sugar pans, and color and suspended solids measurements in the pipe line to control the clarifier. We will also present improvements in software and automation in the lab where a solids particle sizing system has reduced the labor in the lab by one person on all shifts. Additionally, the measurement of sugar crystal size and shape in liquid slurry regardless of concertation can now be measured using the patented auto dilution method in both lab and production settings. Lastly, software improvements in recent years now allows a dual particle distribution output to fully control the process of growing large grain crystals in the 2000-micron range and above.

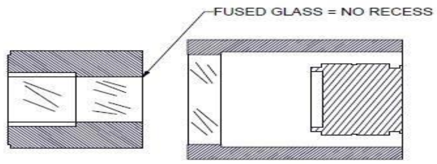
Introduction

Dynamic imaging operates on the basic principle of capturing real time images of a process, having software analyze the images for particular features and conditions and providing outputs upon which the operator can make decisions based on the data and the visual output from the camera. This paper outlines the relevant applications of dynamic imaging within a sugar production facility and compares it to other industry methods used. Sugar production processes where this technology can be employed include clarifying, crystallization, centrifuging, and product quality control.

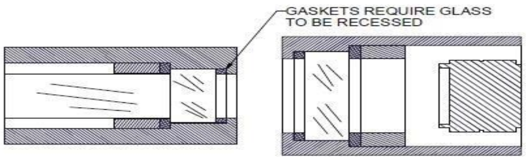
Fundamentals

A quality imaging system depends on the quality of the three building blocks of the system; the process barrier, the imaging sensor and lens combination and the illumination to view the process fluid and particulate. The process barrier should use the fused glass to metal technology to create the transparent pressure boundary required for the light and camera to see through. The glass is fused directly to the metal creating a high-pressure seal that requires no gasket and creates no recessed cavity where eddy currents can develop allowing crystals to stagnate (see Fig. 1). This technology also permits the use of insertion lens tubes for the camera and light which create a measurement zone in the middle of the flow and not along the pipe wall.

The imaging sensor, or camera, is the simulation of the human eyes in the dynamic imaging system. Gigabit ethernet technology, incorporating high color sensitivity, and designed specifically for process vision applications along with lenses designed to conduct a well-focused image to the sensor are required for optimal resolution of process images. Current technology enables capturing and processing of 15 to 20 images per second which means process information is gathered and converted to analytics at a near real time rate.



CANTY FUSED GLASS



COMPETITION PLATE GLASS

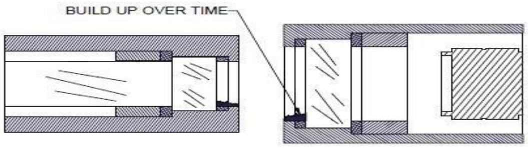


PLATE GLASS WITH BUILD UP

Figure 1. Fused glass to metal process barrier

Perhaps the most critical component of these building blocks is the illumination system. Without the proper consistency, or style of light, the imaging sensor cannot perform optimally. Good results hinge directly on the screen wide consistency of the illumination as well as the intensity. LED technology is used to provide pixel to pixel consistency within 1% which enables the imaging sensor and software to detect the same way everywhere in the field of view and throughout the duration of the analysis.

The technology is represented in the schematic in Figure 2 in two typical configurations where either front light or back lighting is used depending on what the application requires. Additionally, either configuration is available as fully rated explosion proof or weatherproof to meet all application needs.

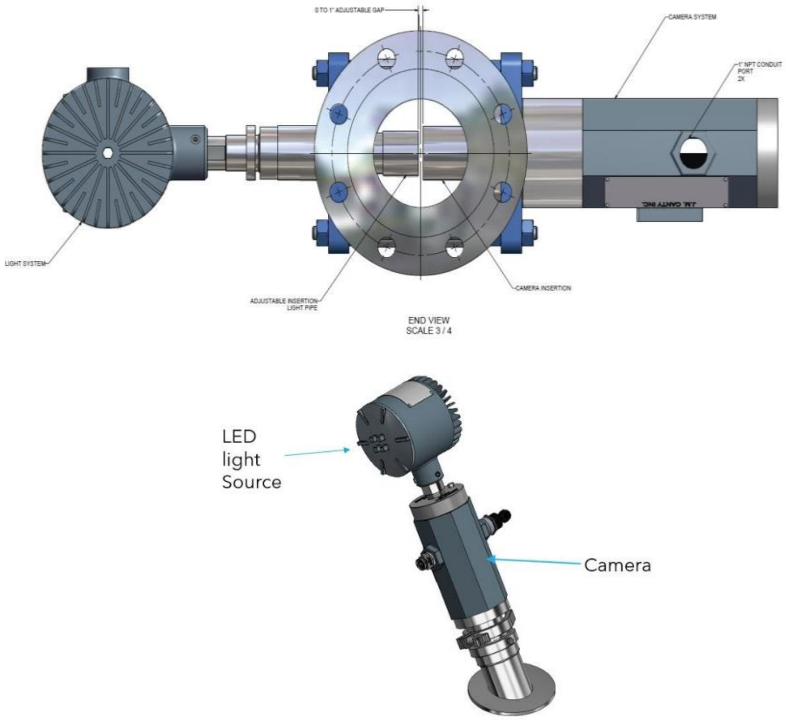
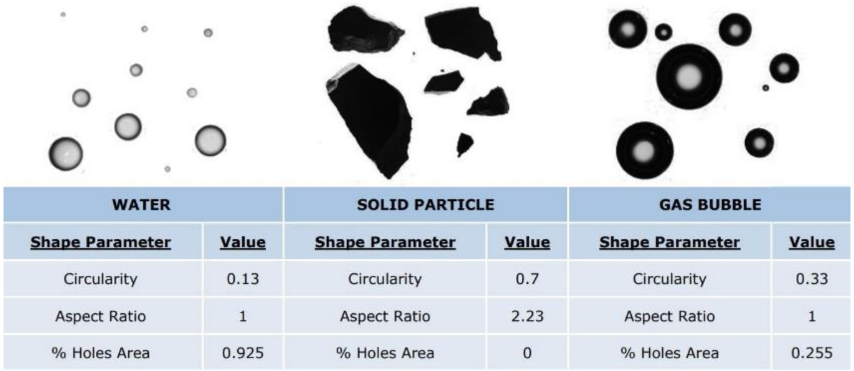


Figure 2. Typical Imaging Systems

Application 1: Clarifier

How and where can the use of this technology benefit the quality and overall cost profile of the product? We start at the clarifier. Installing an imaging system into the liquor discharge line provides advantages over current turbidity or light obscuration technologies. A common fault of non-visual instrumentation is the inability to discern between solids and gas bubbles. The bubbles get counted into the data producing error in the result. Vision technology has the ability to classify gas bubbles apart from solids based on particle morphology thereby preventing them from disturbing the solids analysis. Figure 3 shows particles that have different shapes and therefore can be measured separately when a dynamic imaging system is used to make the measurement. The graphical output in Figure 4 shows the effect bubbles have on a turbidity reading.



WATER		SOLID PARTICLE		GAS BUBBLE	
Shape Parameter	**Value**	**Shape Parameter**	**Value**	**Shape Parameter**	**Value**
Circularity	0.13	Circularity	0.7	Circularity	0.33
Aspect Ratio	1	Aspect Ratio	2.23	Aspect Ratio	1
% Holes Area	0.925	% Holes Area	0	% Holes Area	0.255

Figure 3. Particle classification based on morphology

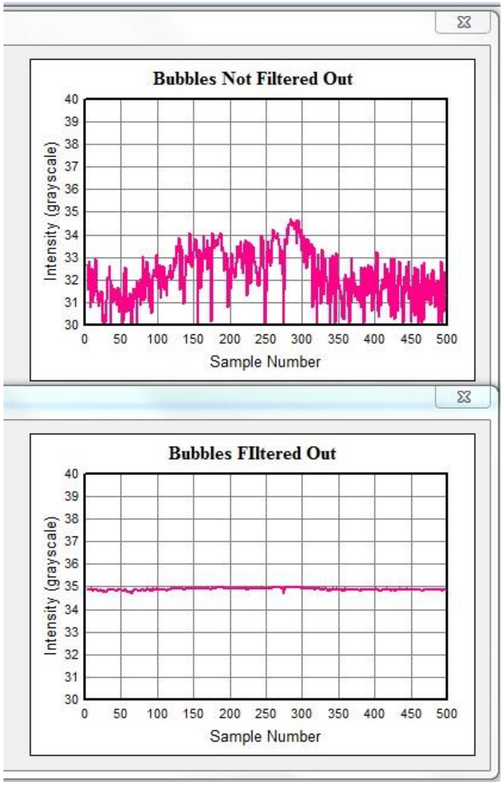


Figure 4. Intensity (turbidity) results with and without air bubbles filtered out

The data in figure 4 is a measure of 180-degree light transmittance through the process fluid. As solids/bubbles increase the intensity read drops. It is apparent from the filtered and non-filtered result that the bubbles have a significant effect in skewing the turbidity reading. One of the key benefits of clarification is the reduction of turbidity[2] and therefore it is important to know the actual turbidity in the clarified liquor so the process can be maintained at an optimal level. When the true turbidity is masked it is difficult to make process judgments from batch to batch.

Application 2: Crystallization Analysis

A second point of application is the vacuum pan (Fig. 5) where crystallization takes place[1]. There are several sight glasses mounted in a vertical arrangement to assist the operator in determining the liquor level during boiling. This is a significant opportunity to acquire cost savings. Fused glass technology provides a sure way to seal the sight glass which is critical in maintaining the vacuum at the least cost. Traditional sight glasses are usually a plate of glass retained by a metal flange. Bolting a piece of glass into a flanged port creates large, uneven residual stresses on the glass. Over torquing can fracture the glass, now or later, and not enough torque will allow the vacuum to leak. The fused glass to metal sight glass consists of an inner glass portion which is fused to a surrounding ring. This places the glass under several thousand pounds of compression making it stable and not subject to tensile stresses. The retaining flange sits on the metal ring and so there are no residual stresses applied to the glass. In addition, the retaining flange can be tightened down sufficiently to create a leak proof seal.

Figure 5. Typical Sugar Pan[3]

The difference in energy consumption per liter is demonstrated in the following analysis. The energy to heat a mass of water to its boiling point can easily be calculated using this formula:

$$Q = m\ Cp\ (T2 - T1) \qquad \text{Eq. 1}$$

Where m = mass, Cp = specific heat, T2 = final temp, T1 = starting temp. A sample calculation is provided below for ambient pressure, 14.7 psia, and 2.9 psia vacuum conditions:

To heat 1 litre of water from 20°C to a boiling point of 100°C (ambient; 14.7 psi) Q=1(4.186)(100-20) Q=334.88kJ / 0.093kWh per litre

To heat 1 litre of water from 20°C to a boiling point of 60°C (vacuum; 2.9 psi) Q=mCp(T2-T1) Q=1(4.186)(60-20) Q=167.44kJ / 0.047kWh per litre

In charted form:

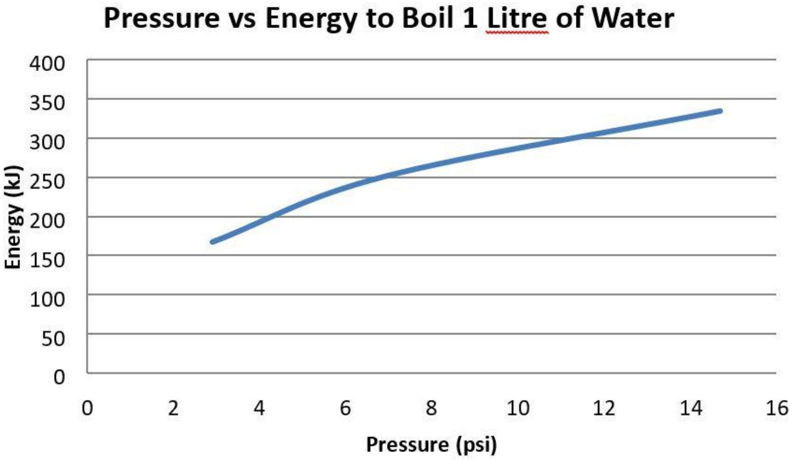


Figure 6. Boiling Energy of Water at Various Pressures (Absolute)

From the chart it is apparent that the energy required for boiling is proportional to the integrity of the pan’s pressure boundary. If there are leaks, costs go up.

Additionally in the vacuum pan the crystallization process through the various growth stages can be monitored. Traditionally a small sample would be removed and visually analyzed by the operator. This method is quite subjective and does not provide a quantifiable analysis of the sugar crystals. Vision technology can provide the on screen visual for the operator and can also provide an objective analysis of the size and concentration inside the pan at any time from initial seeding through to full growth. A proper instrument will insert through a single vessel port and provide illumination and camera sensor in one package. It is important that the instrument not be a flush mounted type instrument, rather it must insert into the process to be away from the wall and any eddy effects or low temperature areas where growth may lag the remainder of the strike.

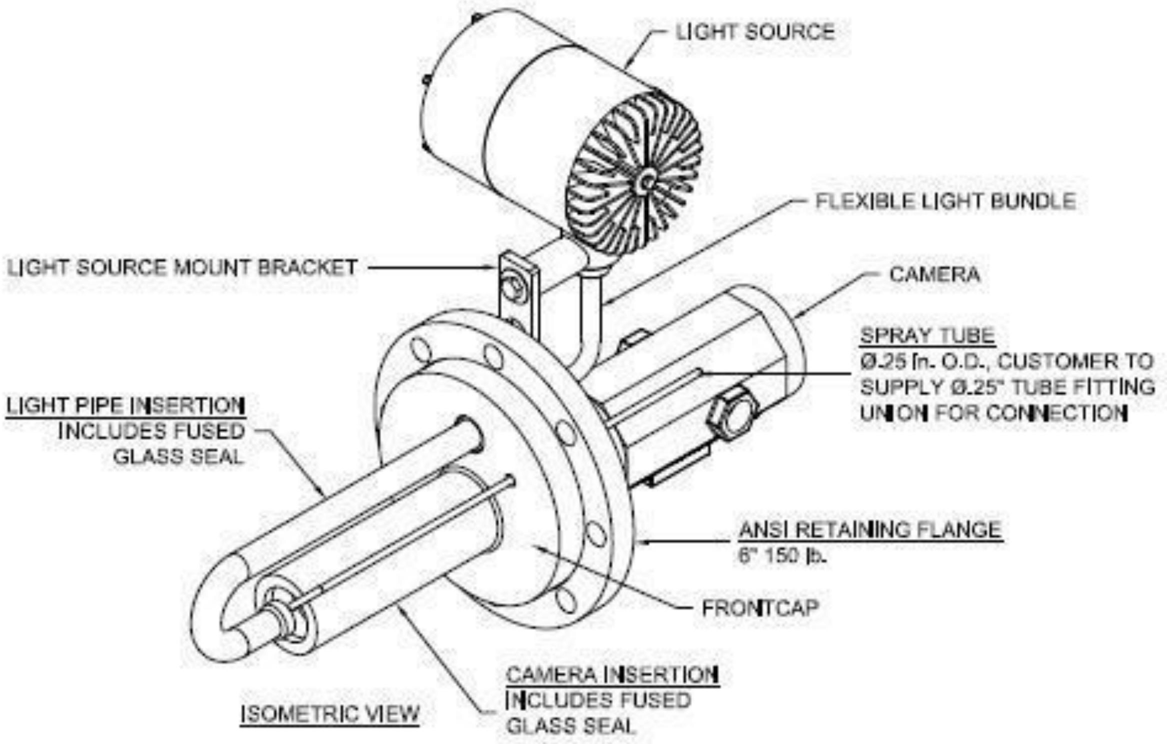


Figure 7. Typical Insertion Style SugarScope

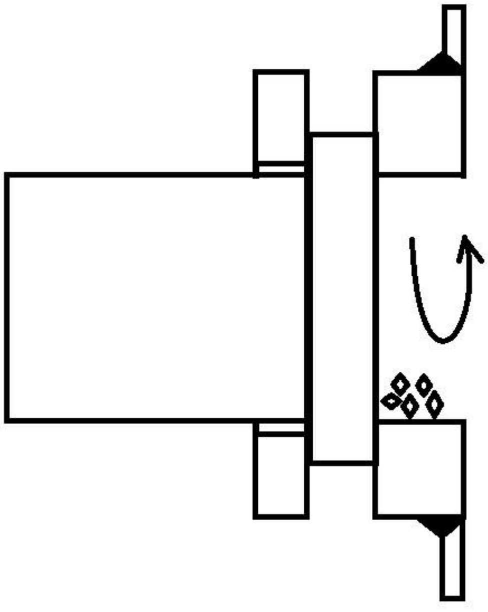


Figure 8. Poor Installation

The following figures show the crystallization process at various time points beginning with the detection of initial seeding.

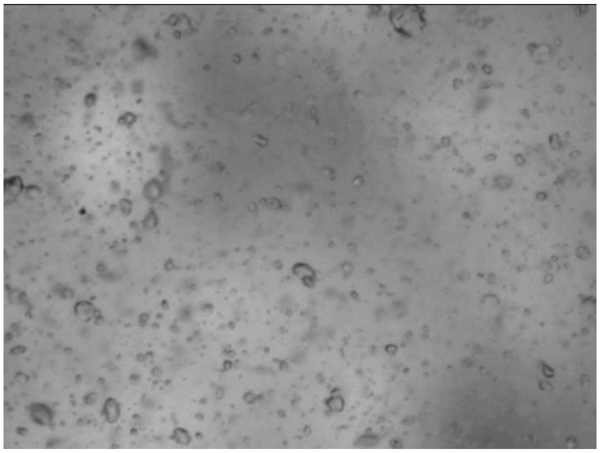


Figure 9. Initial Seeding

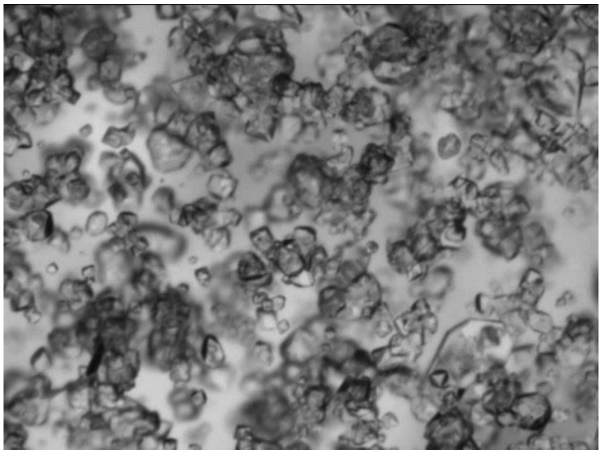


Figure 10. Seeding + 30 Minutes

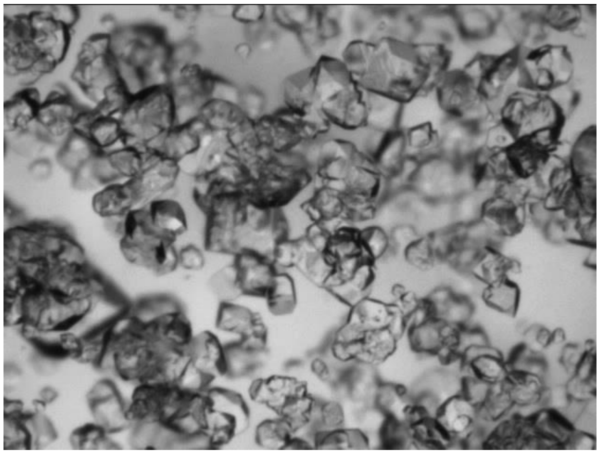


Figure 11. Seeding + 60 Minutes

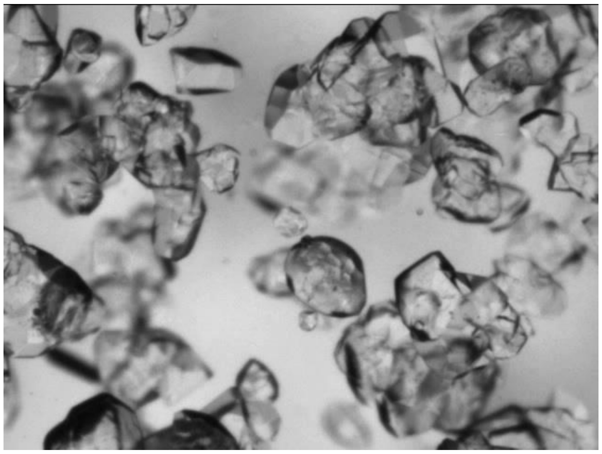


Figure 12. Seeding + 150 minutes

The images are digitized and then sized by minor diameter. There are multiple particle characteristics captured and computed for each particle which can be used to filter for specific features. Data reported includes major/minor diameter, aspect ratio, perimeter, area, volume and circularity. Figure 13 shows a typical image with particle analysis performed on sugar crystals. Note there is a gas bubble in the top left corner of the analysis frame and as mention when discussing turbidity measurements, this particle has morphological differences than the sugar crystals and therefore will not be report in the crystal size data because the software can identify it as a gas bubble and can be trained to exclude bubbles from the crystal size data. In figure 13, the purple graph is the volumetric particle distribution and the red plot is particle shape data namely aspect ratio (y-axis) as a function of minor axis (x-axis). The analysis occurs in near real time as the process is ongoing. Outputs are available on a minute-to-minute basis. The software can be set to show trending, such as D10, D50, D90, and/or a complete distribution of size by minor diameter or any other characteristic desired. Additionally, in recent years advancements in imaging sensors and image analysis software has allowed for measuring and controlling bimodal particle distributions which is an important added capability for crystallization monitoring of large grain crystals. In additional to the visual verification and the image analysis, a major advantage of vision technology is that the software can undergo machine learning to better discern the process based on the operators' observations and inputs.

	MEAN	MAX	MIN	MEDIAN
MINOR DIAMETER	9.4414	114.9040	1.4112	4.8921
MAJOR DIAMETER	28.5150	294.1944	1.4112	16.4934
ASPECT RATIO	3.4155	45.0000	1.0000	2.8105
BOUNDING RECT WIDTH	28.5150	294.1944	1.4112	16.4934
BOUNDING RECT HEIGHT	9.4414	114.9040	1.4112	4.8921
BOUNDING RECT DIAGONAL	30.1847	297.0832	1.9957	17.5849
PERIMETER	70.1424	825.4292	2.8223	35.6952
CONVEX HULL PERIMETER	58.1885	488.7082	2.8223	30.9306
HOLES' PERIMETER	NaN	0.0000	0.0000	NaN
MAX FERET DIAMETER	28.6347	294.2010	1.9957	16.5412
EQUIVALENT ELLIPSE MAJOR AXIS	30.8090	371.5625	1.2928	15.6808
EQUIVALENT ELLIPSE MINOR AXIS	5.6730	101.1765	1.2928	2.8016
EQUIVALENT ELLIPSE MINOR AXIS (FERET)	8.9802	115.6781	1.2705	4.8899
EQUIVALENT RECT LONG SIDE	30.2500	410.6634	0.7056	13.7942

Dv06	12.9719
Dv10	15.9635
Dv20	23.1865
Dv30	29.3743
Dv40	36.5237
Dv50	44.4481
Dv60	53.3479
Dv70	62.8955
Dv80	75.8474
Dv90	91.6981
Dv96	110.6947
Dv100	114.9040
Dn06	1.4112
Dn10	1.4112
Dn20	1.4112

Total Count 7582 Total Area 1.78368E Total Volume 5.64242E PPM 480.135 PPML 68543.5 MA 44.4481 CV 68.2328

13:27:17.472
11/12/2020

Configuration File	ED&F Light Configur
Classification File	Sugar W Gas.clf
Camera Temperature	
°F	0.00
°C	0.00
Acquisition Statistics	
FPS	5.05
Current Frame	47
Batch #	0
Batch Frames	NaN
Batch Particles	100000
Batch Time (s)	NaN
Video Statistics	
Max Frames (AVI)	387
Analysis Statistics	
Start Time	11/12/2020 13:26:58
Elapsed Time	0 00:00:19
Pixel Scale Factor	1.4112
Total Particles	8116
Accumulated Particles	225
Analysis Data	
Mean Focus Rejection	30.0541
Avg. Particles/Frame	216.2
Avg. Area/Frame	48208.3
Pixels % Frame	0.34
Speed Statistics	
Disk Stream Speed (ms)	8
Classification Status	OK
Classification Time (ms)	10
Calculation Time (ms)	10
Pumps	
Pump 1 Speed (%)	
Pump 1 Rate (mL/min)	
Pump 1 mL Pumped	
Pump 2 Speed (%)	
Pump 2 Rate (mL/min)	
Pump 2 mL Pumped	
Automated Analysis	
Dilution Ratio	
Sample Size (mL)	
Cleaning	
Auto-Clean Timer (s)	
Feeder	
Feed Rate (%)	

Video Analysis: Taking measurements...

Figure 13. Software analysis of crystals

Assessing the benefits of monitoring and analysis of the crystallization process through the use of vision technology can now be quantified in a meaningful way. An estimated calculation is provided to illustrate savings that may be achieved with the installation of the technology on the vacuum pans.

- Reduction of boiling times / increase of throughput (up to 33%)
- Increase yield by 10%
- Reduction in annual water/steam usage (up to 33%)

Total cost savings depend upon current operating efficiencies, however a conservative estimate of labor, energy and resource savings, plus yield increase, would amount to approximately $50,000 per pan per year.

Application 3: Centrifugation

After crystallization, vision systems can be used in the optimization of both batch and continuous centrifugation process. Figure 14 shows a view inside a typical centrifuge. In batch centrifuges, the vision system provides the slurry level by tracking the edge where contrast is significant between the slurry level/cake and centrifuge basket. Cake wetness is measured by the amount of light reflection in a region of interest over the cake's surface that the vision system detects. The amount of reflection is proportional to the wetness of the cake and therefore allows for wash cycle optimization. Similar to tracking slurry level in a batch centrifuge, in a continuous centrifuge the color line can be tracked and allows for feed conditions to be controlled and automated to maintain an optimal color line. Figure 15 shows typical outputs over time when monitoring a centrifuge with a dynamic imaging system.

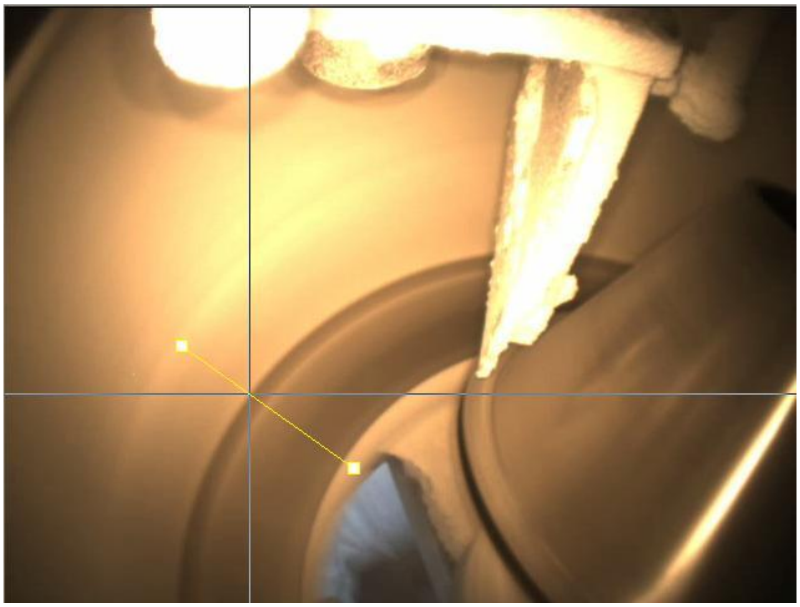


Figure 14: Typical view inside a centrifuge with slurry level measured

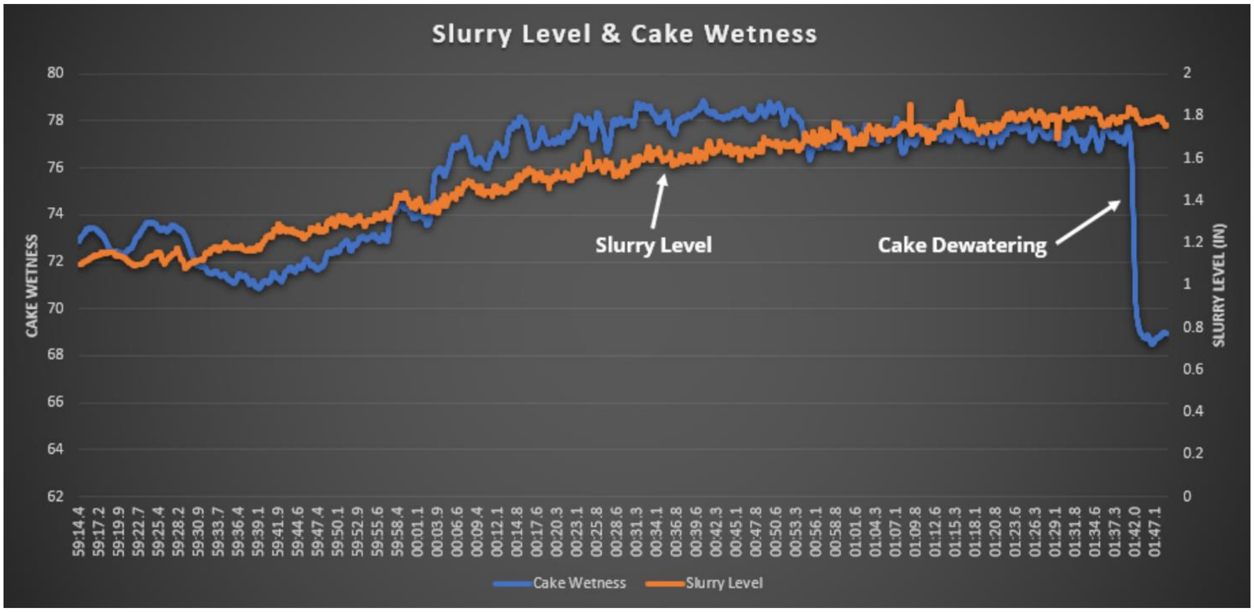


Figure 15: Real time tracking of slurry level and cake wetness during a centrifugation

Application 4: Laboratory Crystal Size and Shape Detection

Although much of the focus thus far has been on in process monitoring of process parameters, dynamic image can also be used to measure particle size and shape of sugar crystals in a laboratory setting. By using a feed tray to automatically pass a particle cascade between an illumination source and camera, 2D images of the crystals can be captured and measured for size and shape data. Given that the speed of the feeder can be controlled based on the number of crystals seen on the image, overlapping crystals on the image can be avoided allowing each crystal to be independently measured for particle size and shape while also allowing analysis to occurring as quickly as possible. Figure 16 below shows a typical layout of a dynamic imaging machine to perform this measurement.

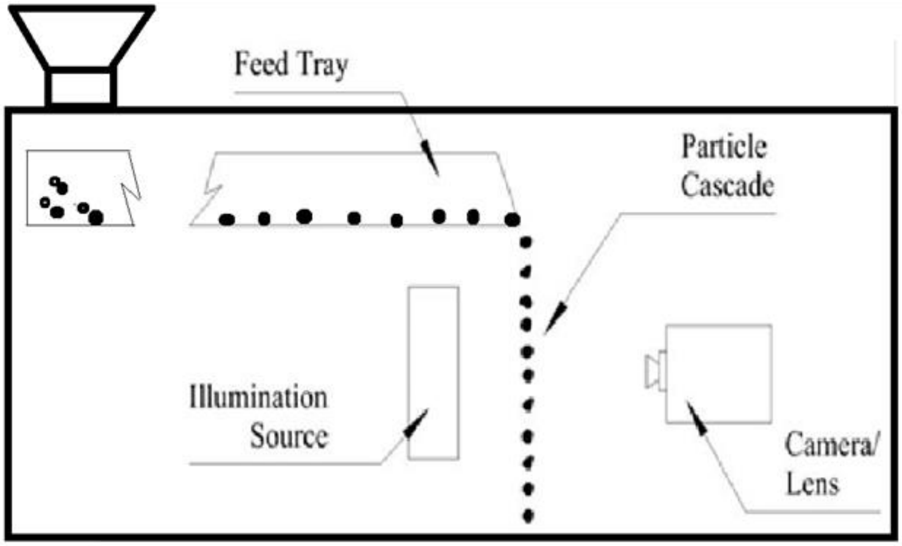
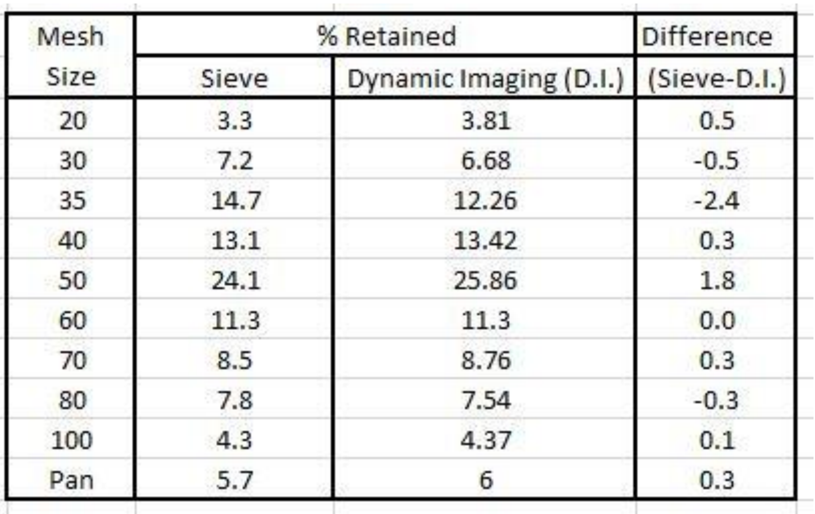


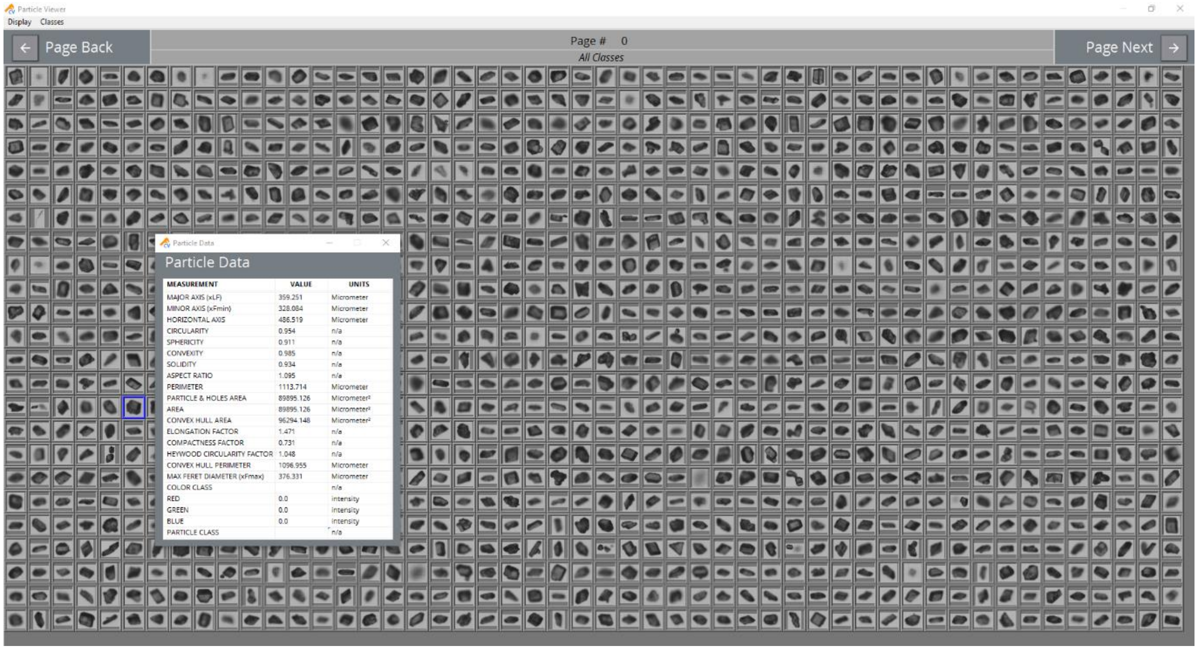
Figure 16: Typical layout for measuring size and shape of dry crystals

The measurement can be correlated to sieves as shown in figure 17 allowing for it to viable replacement for sieving currently done in the laboratory for quality control. It has the added benefits over sieving of increased throughput compared to sieves because analysis only takes a few minutes per sample, lower labor costs because the analyzer does not require screens to be cleaned after each analysis, and provides particle shape data which sieving does not provide. Particle shape data can provide vital information to understanding how the process is performing. Figure 18 shows particles of all different shapes and sizes that were gathered in an analysis of a dry sugar sample.



Mesh Size	% Retained		Difference
	Sieve	Dynamic Imaging (D.I.)	(Sieve-D.I.)
20	3.3	3.81	0.5
30	7.2	6.68	-0.5
35	14.7	12.26	-2.4
40	13.1	13.42	0.3
50	24.1	25.86	1.8
60	11.3	11.3	0.0
70	8.5	8.76	0.3
80	7.8	7.54	-0.3
100	4.3	4.37	0.1
Pan	5.7	6	0.3

Figure 17. Sieve to Dynamic Imaging Comparison



Particle Data

MEASUREMENT	VALUE	UNITS
MAJOR AXIS (xLF)	359.251	Micrometer
MINOR AXIS (xFmin)	328.064	Micrometer
HORIZONTAL AXIS	486.519	Micrometer
CIRCULARITY	0.954	n/a
SPHERICITY	0.911	n/a
CONVEXITY	0.985	n/a
SOLIDITY	0.934	n/a
ASPECT RATIO	1.095	n/a
PERIMETER	1113.714	Micrometer
PARTICLE & HOLES AREA	89895.126	Micrometer^2
AREA	89895.126	Micrometer^2
CONVEX HULL AREA	96294.148	Micrometer^2
ELONGATION FACTOR	1.471	n/a
COMPACTNESS FACTOR	0.731	n/a
HEYWOOD CIRCULARITY FACTOR	1.048	n/a
CONVEX HULL PERIMETER	1096.955	Micrometer
MAX FERET DIAMETER (xFmax)	376.331	Micrometer
COLOR CLASS		n/a
RED	0.0	intensity
GREEN	0.0	intensity
BLUE	0.0	intensity
PARTICLE CLASS		n/a

Figure 18: Example crystals detected and measured during analysis

Lastly, dynamic imaging can also be performed in a laboratory setting on a liquid slurry where dilution is automatically performed on the slurry to again optimize the analysis, minimize run time, and avoid overlapping particles. This can be particularly useful when particle size and shape data is needed on a liquid slurry sample and the necessary resources are not available to perform other methods that require flammable solvents and additional equipment to allow for safe use of those solvents.

Conclusion

In recent years driven by many advancements in hardware and the machine learning software, dynamic imaging has become a very powerful tool. This tool has been and will continue to be used to optimize sugar production by monitoring and automating the process and laboratory measurements. Turbidity quantification, crystallization monitoring, centrifuge control, and particle size and shape detection are some of the many applications it has been and will continue to be utilized in.

References:

1. Southern Minnesota Beet Sugar Cooperative, ‘Crystallization’, Retrieved from http://www.smbsc.com/OurSugar/SugarProcess/Crystallization.aspx January 7, 2016.

2. Mkhize, S. C., Davis, S. B. 2004. Raw Sugar Filterability Improvements With Syrup Clarification. Proceedings of the South African Sugar Technology Association.

3. Southern Minnesota …, ‘Crystallization’.