Cutting Energy Costs and Speeding Manufacture of Cosmetic Formulations Using Novel Mixing and Monitoring Methods

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ABTRACT

Efficient manufacturing practices must take into account both the energy costs of making a batch as well as the factory throughput. Reliance strictly on the former will improve only one dimension of profitability since the opportunity costs of undelivered product must be part of the gross margin calculation.

This paper describes both the technology and the methods used by one manufacturer to simultaneously decrease energy expenditure and increase productivity. The key hardware elements are a novel mixing/milling machine that processes colloidal mixtures with high efficiency, coupled to an optical analyzer which provides real-time status information. The mixer and analyzer can be deployed individually and result in significant production and energy benefits. The synergy of the pairing of these two capabilities assures that products are in-process for an optimal amount of time, keeping energy costs to a minimum and assuring high quality products. The combined technology opens the door for a peak shaving option.

The presentation will conclude with a discussion of full-scale automation of the procedure which, when fully implemented, allows for further productivity improvements and reduced electricity costs by moving manufacturing to off-peak hours even with a skeleton staff.

Background

Competitive pressures in the cosmetics manufacturing marketplace often appear to push companies in opposite directions. On the one hand, consumers have become increasingly sophisticated, demanding consistently high quality products. They want their colors to be dependable, the texture and consistency to be just right and the durability and shelf life reliable enough to accommodate their changing moods. On the other hand, production costs need to be kept down, not simply to remain competitive at the sales counter, but also to maintain high gross margins and sustain profitability, essential to keeping the investment community satisfied.

Increasingly obvious to many is that the upward pressure of energy prices may be a structural feature of the international financial community and that the cost of electricity is more likely to rise in the next decade than to fall. Faced with these conflicting problems Kolmar Laboratories jointly with NYSERDA chose to investigate the possibility of making quantum changes in their manufacturing approach. Rather than just replacing a motor here or a pump there, a decision was made to undertake a full change in the way a particular product is manufactured.

Critical features necessary for such a program were:

- *Autonomy*. Whatever would be modified would initially have to be local, restricted to a particular product or category of products, and non-disruptive to the ongoing operation.

- *Accountability*. The project needed to be championed by a true-believer at a senior level, especially since that individual would continue to be responsible for the ongoing routine operation elsewhere in the plant.
- *Measurability*. Quantitative measures of cost reduction and product improvement would be essential if there is to be a convincing argument that new ideas are any better than what they endeavor to replace.

This paper documents efficiencies obtained from two tools:

1. A versatile mixer/miller machine called the All-In-One, AIO.
2. A near-Infrared spectral analyzer used to make real-time measurements of mixtures, called the Real Time Optical Analyzer, RTOA.

A case study is presented that employs these two tools operating together to optimize a particularly difficult process. This effort is a work in active progress and so the full benefits of the pair of new tools are yet to be fully quantified. However, it needs to be pointed out that in many cases use of either the AIO or the RTOA will have salutary effects on process performance. In fact, detailed energy calculations attributable to using the RTOA alone as well as estimates of energy savings for the combination of the AIO + RTOA for an earlier configuration and for the current configuration at Kolmar are given in the second half of the paper.

The Challenge

The simplest way to recognize a quality improvement, one for which even the most ardent skeptics would have to nod their heads in admiration, is to manufacture a product that is notoriously difficult to make to specification. Such a product was selected; it turned out to be a skin cream. Traditionally, the manufacture of this cream is a two-stage process. Initially coarse pellets must be ground and dispersed into a fluid matrix. Next the fluid needs to be viscosified to produce a cream. Given the history, demonstration that this product could be made routinely would provide a compelling argument for acceptance of the innovative approaches under investigation. Three issues need to be confronted.

Problem number one is how to make and disperse finely ground particulates in a cost-effective manner. Since these particulates are the primary active ingredient, fine grinding is critical from both an esthetic and functional point of view. With really small particles the consumer enjoys a product that feels smooth and silky. Additionally, the smaller the particles the larger is the surface area per unit mass of active ingredient. In essence, the key component is not locked up inside a large shell where it does not come in contact with the skin. Hence, the manufacturer can reduce the concentration of expensive active ingredient while maintaining product efficacy. Resolution of this problem delivers two simultaneous benefits: increased customer satisfaction and decreased material costs.

Problem number two is to assure delivery of freshly prepared premix as rapidly as possible to an emulsifier. As mentioned before, the liquid needs to be transformed into a cream. Such an alteration comes about when additional components are added to the premix and the entire system is placed under vacuum to eliminate bubbles. Interestingly, the premix chemistry is delicate in that the ground and dispersed active ingredient will reverse the first stage of manufacturing and reagglomerate if allowed to sit for extended periods of time.

Problem number three is that this process is subject to a variety of "unexpected" turns of events. Homogeneity of the dispersion is a particular concern, so too is reversibility of the milling process. Consequently, traditional manufacture of this cream has demanded an undue amount of attention, soaking up altogether too much technician time that could be spent on other activities.

The Solution

The project leader and the NYSERDA-supported scientists and engineers worked jointly to map out a strategy to respond to this particular challenge. While the team was committed to resolving the particular problem placed before it, members felt strongly that an acceptable solution must be flexible enough to accommodate a host of other manufacturing concerns. In other words, the sought-after solution needed to be reconfigurable to respond to future opportunities.

It quickly became clear that the method of milling needed updating with a state-of-the art technology. To respond to problem number one, Sigma Engineering (White Plains, NY) designed and fabricated the All-In-One Mixer/Miller (AIO) unit shown in Figure 1. The AIO creates a vortex which mixes the components in a vat such as the one shown at the right side of Figure 2. In that figure the mixing stalk is obscured by the vessel itself.

At left is the mixing shaft with the bead basket at its bottom. This assembly is attached to the cross-member, with the Sigma logo, that can rise to allow a mixing vessel to be moved in next to the control panel. The active mixing shaft is then lowered into the vat and the unit is ready for operation.

Figure 1. The All-In-One Mixer/Basket Mill

The solution to problem number one is utilization of the AIO. Conversion from colloid milling, the core manufacturing method done in the old way of making the cream, to bead milling achieved multiple goals. The primary one, of course, was in improving the fineness of the grind. Additionally, the time to reach completion dropped dramatically, as much as a factor of 5 for the process considered. Finally, the net energy consumption was considerably reduced.

The solution to problem number two was to move the two process units close to each other and affect a direct transfer, as shown in Figure 2. Ideally, the AIO would have been the place to complete the emulsification. This could have been the case were the unit to have been made vacuum tight, a definite possibility. But in the absence of that degree of versatility, the second best choice is to place the emulsifier next to the AIO and to pump the low viscosity premix over the shortest possible route to the vacuum mixer. In practice the approximately 100 gallons is moved in under 45 minutes during which time very little reaggglomeration occurs.

The solution to problem number three is actually a *suite* of solutions. The first part is the RTOA which is based on a near-Infrared spectrometer that is coupled directly to the pre-mix vat with fiber optic cables. Two windows, or portals, through which the light could penetrate into the mixture, were built into the vessel. Although not yet implemented, plans for additional observation ports, particularly in the piping to the emulsifier (homogenizer), are planned. Since the instrument can be multiplexed, i.e. multiple fiber optic probes may operate virtually simultaneously from the same spectrometer, the benefits of several analyzers can be derived from a single unit. Properly configured, the RTOA can detect the state of the mixture as the process is run.

But simply knowing the condition is not enough. A critical second part of solution number three is the addition of a programmable logic controller (PLC) to actuate suitable consequences. In other words, the combination of RTOA and PLC can be empowered with algorithms to recognize mixing states and issue instructions. These commands range from shutting off the motor upon completion of mixing to opening valves and pumping out product. The overall suite provides both the supervisory and interventional needs of the manufacturing process.

Foreground shows vessel for the AIO with the mixing shaft descending from the upper right of the figure. This vat is for grinding premix and making the dispersion. The covered vessel on the left is vacuum-tight and is the site for emulsification of the premix, a process that turns the low-viscosity fluid into a cream. A computer and the optical analyzer can be seen on the table beneath the shelf at the center of the scene.

Figure 2. The Tandem Vats

Typically, mixing/milling times are based on heuristics derived from experience gathered from laboratory measurements. By their very nature, these data were obtained discontinuously in time and are expensive and time consuming to do routinely during manufacture. By contrast, the addition of an on-line analyzer makes available a continuous monitor, one which actually examines the contents of the vat, not just a thermodynamic variable like temperature or pressure.

To get a better picture of this, consider the data of Figure 3, which shows a plot of light intensity emerging from the analyzer as a function of mixing/milling time. Two major abrupt changes can be seen, one at about 1500 seconds and the other at about 2800 seconds. It is straightforward for an operator (including the controlling software!) to notice that during the first 1500 seconds nothing is happening. At least nothing is changing during this period of stability. Basically, the mixer is being run with little or no benefit during this time period, suggesting that this part of the process could be curtailed, saving both energy and time. At the jump, however, *something* is happening, and the analyzer can readily pick up exactly what is occurring.

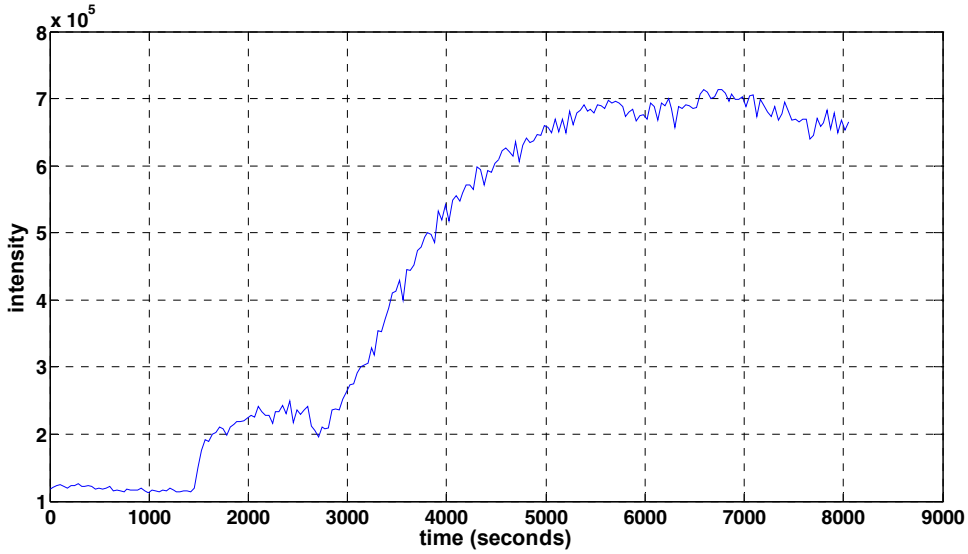
But what exactly is causing this jump? Recognizing that the analyzer can provide a near-Infrared spectrum, information beyond simple intensity is available. In fact, the spectrum of a sample is entirely dependent on the chemical composition of that sample (Dekker 2001). Figure 4 shows the *spectral* output of the analyzer. What is seen is a single-beam spectrum, which means that the intensity of light returned to the analyzer is plotted as the y-axis, and the wavelength of light is plotted as the x-axis. The instrument spans a wavelength range from 1100 nm (at pixel 1) to 1900 nm (at pixel 256), but for ease of use, the simpler pixel number is often preferred.

Now consider how these spectra shown in Figure 4 change in time. In fact, the spectra rise as time proceeds. In other words, the cluster of spectra near the bottom are taken at the earliest times, i.e. right before the steep rise, and the ones at the top occur at the end of the interval, corresponding the period after the jump shown in Figure 3 at 1500 seconds has finished. Clearly, the chemical composition is changing over this period. Indeed, these spectra correspond to the addition of a component into the vat. While this may be no surprise to the operator doing the addition, the information is recorded and saved for future reference, if needed. Furthermore, if the injection of fresh material were initiated automatically, confirmation of its presence is made possible by these spectral observations.

The jump beginning at 2800 seconds, however, is the most important part of the process, corresponding to the dispersion and grinding of the key additive in the formulation. The data show that the process changes dramatically for about the next 3000 seconds and then tapers off. By about 6000 seconds the signal ceased to change indicating that the AIO milling process had completed its task and that further processing would merely expend time and energy, but have not useful outcome. The gentle dip that begins at 7000 seconds is real and will be discussed below.

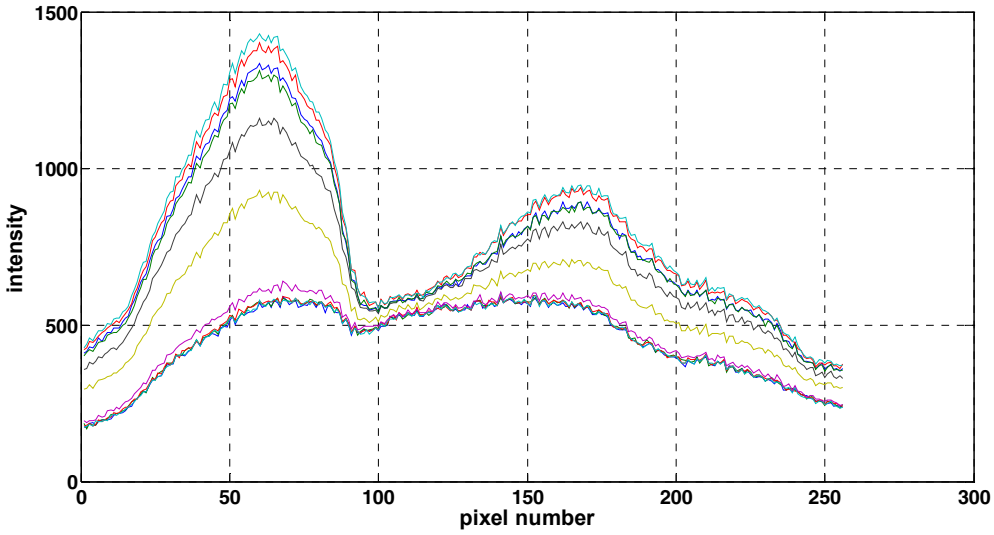
Scattered light was measured by the RTOA for the pre-mix stage of the process. Rising sections of the curve indicate periods of change in the AIO vat, while flat portions represent stable points indicating the completion of that particular stage.

Figure 3. Time Evolution of the Intensity of Light Signal



Spectral data showing that the actual chemistry in the mixing vat changed during the selected interval. The axes are intensity versus pixel number (see text for explanation). At bottom are spectra of the material right before the jump at 1500 seconds shown in Figure 3. Spectra above that show the transition corresponding to the jump. The uppermost spectra show that the system has restabilized to a new overall composition that corresponds to the plateau between 1600 and 2800 seconds in Figure 3.

Figure 4. The Evolution of Chemical Composition



Tying It All Together

Overall, the approach to advanced manufacturing has been to create a decentralized pod, i.e., a self-contained cell. While naturally, an efficient mixer such as the AIO is a potent centerpiece, the cell may be built around whatever mixer is most available for the process. Crucial to the pod approach, however, is the ability to *detect* process variables using the RTOA and *respond* automatically to the needs that are computed by the governing algorithm. By affixing a fiber optic connector to a flow cell, the RTOA can monitor the mixture from any vat. All that is needed is establishment of an external closed-loop flow of the mixture from the mixing vat, through the optical cell and then back into the vat. Then everything operates via the analyzer and control suite run by a single processing unit such as a laptop/PC that initiates and receives data to/from the optical analyzer and a PLC.

In this process the analyzer "sees it all," and problems with the process not necessarily noticed by routine visual observation – and too time consuming to be done in an analytical lab – were detected. For example, what is the reason for the dip at 7000 seconds shown in Figure 3? Could this be an example of the "unexpected" turns of events mentioned in problem number three?

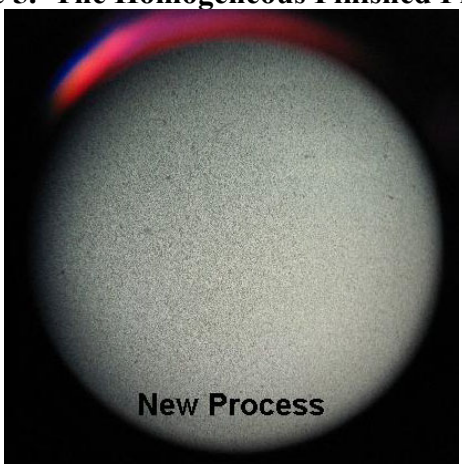
This implementation required two vats to be connected, one for premixing and the other for homogenizing. It had been well-established that the pre-mix, when allowed to sit after milling would begin undoing the grind and start reagglomerating. That is exactly what is being shown by the dip in Figure 3. The mixer was shut off at 6500 seconds, and in the time it took to empty the AIO vat into the *nearby* emulsifier, the process began to reverse itself. Although this regression is minor, cost-effective corrective actions could be taken. In this case a modified transfer mechanism was worked out, speeding up the removal of premix. The objective of squeezing out all the benefit of the AIO grind capability and manufacturing the highest possible quality of the finished product was met. This assertion is validated upon examination of Figure 5, a photomicrograph revealing the uniformity of the finished product.

By monitoring the process to performance specifications, manufacturing becomes tolerant of variations in components and conditions. Future implementations will allow for automatic shutoff of the AIO mixer, opening of the drain valve and pumping of the premix into the emulsifier. In practice, the PLC controls water-jacketing of the mixer vat, so even temperature can be controlled. Nonetheless, the option remains to experiment with temperature and other variables to see if the process can be speeded up while maintaining essential control over the mixing duration through optical measurements.

Our decentralized pod approach can be readily replicated elsewhere in the factory as its merits become more apparent. Eventually, should it be deemed desirable, these pods could be easily linked to a master control system supervising the entire factory.

Photomicrograph of the finished product squeezed between two microscope slides and viewed at 25X. The uniformity – and most importantly the absence of larger particulates – attests to the quality of the overall product.

Figure 5. The Homogeneous Finished Product



Detailed Analyses

Description of Current AIO Hardware

The AIO design allows for mixing, dispersing, and milling (grinding) to be done in a single vessel. The machine is equipped to enable continuous monitoring of mixture composition and particle size. The AIO includes a stainless steel basket containing a volume of ceramic, steel or glass grinding media. Running centrally in this basket is an agitator shaft, which serves to set the grinding media into motion. It is the action of this grinding media on the product slurry, which is passed through the basket that serves to achieve the desired degree of product homogeneity and fineness of grind.

The AIO used in the demonstration project has dimensions of 85" (L) x 35" (W) x 78" (H) and weighs approximately 3000 lbs. The machine frame, manufactured of carbon steel, accommodates the electric drive motor and electrical controls. The product mixing vat is made of 304 stainless steel and is equipped with a water jacket for better temperature control. There is a bottom outlet valve for discharge and safety switches to prevent the possibility of the machine operating without the vessel in place. There are portals installed along the side of the vat, which allow for insertion of the fiber optic probe and taking measurements at different levels in the mixture. The machine is driven with a 30 Hp, 80 amp explosion-proof electric motor which is suitable for operation through a frequency inverter in order to affect variable speed. The motor is rated for operation at 230/460 volts at 60 Hz, 3-phase. The AIO also has a 1 Hp, 3.5 amp motor to turn the sidewall scraper arm as well as a 3 Hp, 10 amp motor to drive the hydraulic pump that lifts the basket up to change beads or remove the vessel. The self-contained hydraulic lift system enables installation flexibility at sites that might not otherwise have a suitable air supply for a pneumatic one.

In order to effectively integrate the AIO into Kolmar's manufacturing process, a raised concrete support platform was built near the homogenizer and the AIO was positioned on top of and affixed to the platform. To match the desired batch size of the skin cream product, a 500 gallon vat (shown in Figure 2) of similar construction to the original 100 gallon one, was built.

Combining RTOA with AIO

Two portals were built into the new vat of the AIO to provide 2 potential sites for attaching a fiber optic probe. The 1.25" (D) x 0.25"(thick) glass windows that enable peering into the mixture are sealed with both gaskets and an epoxy bond that successfully secure the interface and assure leak-tightness. A Teflon support structure was custom built to facilitate optimum placement of the fiber directly on the sight-glass since it had been determined in the lab that this configuration provides the strongest signal to background ratio. Two bolts hold the Teflon disk in place around the portal. With the fiber coupled directly to the vat, measurements are taken with the RTOA, which is operated by a laptop computer. No invasive probe is used.

Energy Evaluation from Adaptation of RTOA

Prior to installing the new technology on the plant floor an energy analysis of using a real-time optical analyzer (RTOA) for control versus using no process control was made. While a full energy analysis of the decentralized approach is still to be undertaken, the rationale for utilizing the RTOA can be seen from the following analogous analysis in which an existing colloid mill and homogenizer were used. It should be noted that an additional third "finishing" step is undertaken in this specific case.

The RTOA system including optical cell, NIR analyzer, fiber optics, and computer was set up at one of Kolmar's larger wet mixing tanks in their Port Jervis, NY facility. This system was run by recirculating product from the mixing vat through the optical cell and back into the vat. The Kolmar mixing system consisted of a propeller mixer (8.5 amp, 3 Hp), homogenizer (57 amp, 25 Hp), colloid mill 23.4 amp, 20 Hp), and recirculating pump (15.5 amp, 5 Hp). Ammeters were connected to the controls of each piece of equipment in order to monitor the electrical draw in real time. The cosmetic product would be manufactured in 3 steps. Table 1 depicts the electric consumption data collected. In the first step, a batch of iron oxide colorant, titanium dioxide and silicone-based materials were mixed and milled for 2.5 hours (according to the historical spec). At 12:20 pm the process began. After 40 minutes (at 1:10 pm) sample 1 was taken. A slide test indicated a few black and red spots, suggesting some residual inhomogeniety and a Hegman test showed a Hegman number of 14, indicative of the material being close to finished, but not yet complete. Simultaneously, the RTOA was indicating signature changes. At 1:42 pm, the RTOA was showing no changes so a sample was taken. This time no spots were seen on the slide test and the Hegman test, a manual measurement of particle size, indicated a level of 10-12, which met the spec. Step 1, completed in 1 hour 22 minutes instead of 2 hours 30 minutes, had savings of 47% due to process control.

In Step 2, Kolmar added a silicone rubber material (from 2:10 – 2:20 pm). The mixing and grinding equipment continued until 2:42 pm when the RTOA indicated no change and that a sample (Sample 3) should be taken. Once again, the slide test was acceptable showing no agglomerations. This step, according to the RTOA, took only 22 minutes instead of the 55 minutes the spec called for resulting in an energy and process time savings of 60%.

For the third finishing step, the batch from Step 2 was pumped to an adjacent tank connected to a prop mixer (9.7 amp max current draw, 3 Hp), sweeper (12.7 amp, 5 Hp), static mixer (0 draw) and pump (15.5 amp, 5 Hp). Ammeters were affixed to the mixing equipment. The RTOA system was re-setup to control this new step.

At 5:19 pm a water phase mixture from a third tank was pumped into the Step 3 tank and circulated through the system and slipstream. This water addition caused a pronounced change in the appearances of the spectral data until the system stabilized at the new composition. By 5:54 pm the water phase was completely transferred into the process tank and the spectra were constant. At 6:03 pm, spectra start to move up and a shape change is seen by the RTOA as a consequence of particle size changes due to emulsification. At 6:15 pm, after 21 minutes, the sensor said the batch was done. This in fact beat the specification which called for about one-half hour of mixing. The system was shut; a successful test was completed.

Using Table 1, the energy consumed in Steps 1, 2 and 3 using the RTOA can be computed: *KWh = [(avg amps of prop + homog + pump) x (230 V) + (avg amps mill x 460 V)] x Run Time hrs./1000* = [(2.7 + 24.0 + 10.3) x (230) + (12.5 x 460)] x (1.37 + 0.37 + 0.35) / 1000
= 14,260 watts x 2.09 hrs / 1000 = 29.8 kWh

Similarly, the energy consumed in Steps 1, 2 and 3 without process control (just following specs) would amount to 14.26 kW x (2.5 + 0.92 + 0.5) hrs = 55.9 kWh.

Thus, the energy savings in these process steps due to use of the RTOA would equate to 26.1 kWh, or a 47% savings.

Table 1. Kolmar Field Test

Time	Propel-ler 1 (amps)	Homo-genizer (amps)	Colloid Mill (amps)	Pump (amps)	Propel-ler 2 (amps)	Sweeper (amps)	Temperature (degrees C)	Comments
12:20 pm								**Step 1 begins**
12:30 pm	2.68	20	10.1	10.5				
12:35 pm	2.73	25	10.3	10.5				Mill @ 40 Hz
12:45 pm							37	
12:53 pm	2.71	25	13.3	10.3			37	Mill @ 60 Hz
12:58 pm	2.73	25	13.2	10.3			39	
1:02 pm							40	
1:10 pm	2.71	24.9	13.0	10.3			41	Sample 1 taken
1:20 pm							43	
1:25 pm			12.8	10.2			44	
1:30 pm							44	
1:35 pm	2.69	24.7	12.7	10.2			44	
1:42 pm	2.69	24.8	12.7	10.2			44	Sample 2 taken batch done
2:10 pm	**2.70**	**24.7**	**12.6**	**10.3**			**46**	**Step 2 begins**
2:20 pm								All Gransil in
2:34 pm	3.0	23.9	12.5	10.3			49	
2:42 pm								Sample 3 taken Done
2:48 pm								Cut off homog.
5:19 pm				**10.4**	**2.85**	**6.4**	**29**	**Start Step 3 – mix not homog.**
5:24 pm				10.4	2.80	6.4	29	
5:54 pm				10.4	4.33	6.4		Water phase in
6:03 pm				10.4	5.20	6.4		Spectra change
6:15 pm				10.4	5.25	6.38	29	Step 3 done

Assuming 3 batches could be done over a 2-shift day, in a 250-day year, 19,575 kWh (26.1 x 3 x 250) would be saved for this one process. Decreased mixing time will result in labor time savings as well. The Kolmar test indicated that the 3 hour 55 minute process could be terminated after only 2 hours and 5 minutes, a savings of 1 hour 50 minutes (1.83 hours). Annually, this amounts to a mixing time savings of 1,372.5 hours.

If the RTOA were applied to all the wet mixing/milling processes at Kolmar, the impact on peak shaving would be significant. At Kolmar, 34% of power demand is for wet mixing. Potentially, 609 kW (0.34 x 1790) of summer peak demand and 493 kW (0.34 x 1450) of winter peak load could shift.

Tests run using the RTOA coupled to the AIO employing bead milling yielded even greater savings than using the analyzer only. One product, a lotion that typically took two shifts (or 16 hours) of conventional colloid mixing to complete was determined to be done in 1.2 hours with an earlier configuration of the new combined technology, representing an energy savings of over 90%. Several other tests were performed on the plant floor using the current configuration shown in Figure 2 to produce a new skin cream product. To make this cream conventionally would require at least 5 hours of mixing/milling and 3 hours of homogenizing. Using the decentralized pod approach cut grinding time down to 75 minutes and homogenizing down to 1 hour. In this case, the synergistic technology combination yielded energy savings of [8 – (1.25+1.0)] / 8 = 72%.

Conclusions

The project demonstrated the following:

- Virtually total control of the process may be ensured by passive monitoring to quality/performance variables using optical and other analyzers. The observations may then be translated into actionable items suitable for making real-time adjustments including longer or shorter mixing times and automated control of product flow from vat to storage.
- Monitoring to performance variables along with a local “pod” or “cell” manufacturing structure permits substantial energy savings by ensuring that the mixing and milling need be done only as long as necessary to make the product.
- On-line record keeping is simplified since data can be recorded during the entire run. If desired, authentication of the chemical ingredients can be performed, and a validation record compiled.
- Automation enables a reduction of staff necessary to monitor the process thereby making it practical to load shift, i.e., to run the process during late-night or early-morning hours when energy costs are lower.
- Pre-existing factory flow need not be disrupted.

This example in the cosmetics industry is easily generalized for any batch process that requires efficient mixing and milling including paints, inks, agricultural chemicals, and pharmaceuticals. While the AIO is frequently the mixer of choice, it is important to realize that the RTOA can be easily retrofitted to any existing mixer, thereby permitting energy savings over a high percentage of the large existing installed mixer base.

References

Dekker, Marcel, *Handbook of Near-Infrared Analysis (Practical Spectroscopy)*, New York, 2001.