Industrial Process Improvements & Energy Efficiency

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ABSTRACT

Industrial facilities and processes are often highly energy intensive, resulting in significant opportunities for improved efficiency and conservation within manufacturing, chemical, and process system operations. An abundance of technical literature and guidance is available on energy conservation for common energy system categories such as HVAC, lighting, and compressed air; however, process operations are frequently overlooked. The reasons include reluctance to directly interfere with production operations, unfamiliarity with technical aspects of industrial processes and systems, and prevailing culture in many industrial plants that assigns a low priority to energy efficiency. Other factors that lead to inefficient energy usage in industrial environments include emphasis on first cost when implementing capital improvements, deferred/reduced maintenance due to decreased operating budgets, and retooling production operations to meet changing business conditions without considering impact to the efficiency of existing facility operations.

Energy-intensive industrial processes that will be presented in which energy efficiency measures were identified, quantified, and, where applicable, implemented include the following:

- Metal processes such as casting, annealing, and hot and cold rolling
- Plastics processing such as extrusion, thermoforming, and injection molding
- Pulp and paper processing
- Film converting
- Process curing and drying
- Food processing operations, such as pasteurization and refrigeration
- Process heating and cooling

Introduction

This paper will highlight examples of several specific industrial process improvement/energy conservation projects, and provide insight into how opportunities were identified, quantified, and, where applicable, implemented, and how they may be applied to similar industrial operations. It is the authors' intent to describe various approaches to data collection, analyses, and modeling in a broad manner rather than in detail in order to illustrate the myriad of practical approaches taken depending on plant needs and available resources. It is also important to state that the majority of this paper is based on the authors' actual and practical industrial experience, as well as observations and conclusions drawn from engineering studies performed by the authors under the sponsorship of the New York State Energy Research and Development Authority (NYSERDA).

Plastics Industry

Plastics manufacturing operations are generally highly energy intensive. Examples include injection molding, extrusion, and thermoforming operations. Opportunities exist for energy efficiency improvements in facility systems, process support utilities, and even at the original equipment manufacturer (OEM) system level. Typical energy-intensive aspects common to plastic plants (excluding power consumption specific to OEM production machinery) include:

- Process cooling
- Process heating (normally electric resistance heating)
- Curing and drying
- Material transfer operations (resin transfer, resin hopper loading, etc.)
- Significant facility internal heat gain from production machinery
- Substantial amounts of process ventilation exhaust

Extrusion

The majority of plastics manufacturing facilities incorporate some form of process cooling into production operations. Extruders require feed throat and barrel cooling, and water and forced air are common media in barrel cooling applications. Extruder subsystems that often require cooling include drive trains and gearbox assemblies depending on the specific type of application. Once the product is extruded through its forming die, it must be cooled below its melt temperature. Production lines that produce rolls of plastic sheet, known as sheet lines, incorporate water cooled rolls to cool and solidify the product as it is extruded. Often, these cooling rolls are by far the largest cooling load (>80%) on the line.

Most manufacturers of OEM extrusion equipment specify the use of relatively cold chilled water for machine and product cooling regardless of whether warmer water will perform adequately. Plants have many opportunities for cooling energy reduction in this area, but quantifying and implementing the measures require investigation and often testing.

At a small manufacturer of extruded polypropylene sheet [CHA 2002a], for years the common practice had been to supply the OEM temperature control systems with 45ºF chilled water produced by small (5-10 ton) portable air-cooled chillers. The chilled water served various heat exchangers that provided cooling to the two extrusion lines' cooling rolls through separate and isolated process cooling loops. For best product quality and process control, the process cooling water loops were regulated to temperatures ranging from 85ºF to 130ºF. Since the process cooling temperatures were relatively high, the opportunity existed to eliminate the need for chilled water and supply evaporatively cooled water directly to the process cooling loops from a closed circuit evaporative cooler (tower). To accomplish this, the plant first had to become comfortable that the water quality from the closed circuit cooler would be adequate for the process. Physical modifications to the OEM temperature control system followed. The heat exchangers were removed and replaced with a piping configuration that permitted direct mixing of 85ºF centrally supplied tower water with individually pumped process cooling water zones.

The energy analysis methodology used for this project utilized basic principles of spot measurement of steady state process parameters that were used to calculate loads and energy consumption for both the base case and the energy conservation measure. To accurately size the new passive cooling system and predict energy savings, the system's steady state cooling load first had to be measured. Although a clamp-on ultrasonic flow meter was available to measure system flows, the piping configuration was not conducive to accurate readings. Therefore in this application, indirect methods were used. Chiller pump power was measured using a clamp-on ammeter and a spot voltage measurement was taken. A power factor of 0.85 was assumed and pump power was calculated based on these measurements. For the specific pump installed in the packaged chiller, the pump curves were used to estimate pump efficiency (η), pressure across the pump was read from installed gauges, and flow was calculated based on the following relationship for centrifugal pumps:

$$\text{Flow (gpm)} = (HP*\eta*3960)/(\Delta p*S.G.)$$

Using the calculated flow values and chiller supply and return temperatures (measured using a non-contact infrared thermometer reading pipe temperatures), system cooling loads were calculated using the following relationship:

$$\text{Load (BTU/hr)} = 500*GPM*\Delta T$$

With steady state loads calculated, base case energy usage was subsequently calculated using measured chiller and pump power extrapolated over a one year period using 8,760 operating hours with a line utilization factor applied (92% for line #1 and 71% for line #2). The utilization factors were provided by the plant based on production records.

System energy consumption for the new passive cooling system was predicted using a spreadsheet bin analysis that accounted for new system circulating pump, closed-circuit cooling tower spray pump, and tower fan.

The resulting system operates efficiently, with no negative impacts. The modifications resulted in an annual energy savings of 158,000 kWh with a 5.7 year payback (3.6 years with NYSERDA incentive). Although this payback relative to energy savings alone is higher than is sometimes acceptable in an industrial setting, this project is a good example of how secondary benefits may provide management with enough intangible incentives to proceed with implementation. In this case, the use of air-cooled chillers in the extrusion area resulted in summertime temperatures well over 100ºF resulting in extremely uncomfortable conditions for employees. By eliminating the chillers, room temperatures rarely exceed 85ºF during summer resulting in improved labor relations, employee comfort and productivity improvements.

Injection Molding

Process cooling. Like extrusion, plastic injection molding operations are energy intensive. Injection molding machines require water cooling for hydraulics and solidifying the melt within the mold cavities between injection cycles. In the case of hydraulic oil coolers, relatively "warm" cooling water (80ºF-95ºF) will almost always be sufficient since oil temperatures are typically warmer. Mold cavity cooling is typically achieved using unitary temperature control units (TCUs) that incorporate semi-closed loop water systems that circulate water through the molds. Under stable production, mold water serves as the cooling medium for the product, and normally, the TCUs are in the "cooling mode", bleeding chilled water or cooling tower water into the mold cavities as-needed to achieve desired temperatures. During system startups, and occasionally during steady state operations, mold water is heated to facilitate production.

Injection molding plants provide cooling water to the lines using one of the following sources:

- Low-temperature chilled water produced at and distributed from a central chilled water plant
- Low temperature chilled water produced by packaged, air-cooled, unitary process chillers
- Evaporatively-cooled process water from a cooling tower or closed circuit cooler

For the first two sources, opportunities may exist for energy savings. Cooling systems that utilize chilled water (45ºF-55ºF) are common, although usually unnecessary and wasteful since process temperatures are, in most cases, easily achieved using "warm" cooling water. When packaged, air-cooled, unitary process chillers are used in plants that are air conditioned for employee comfort or process control, energy waste is higher, since process heat of rejection is dumped to an air conditioned space and must be removed by the plant's HVAC system.

In August 2002, CHA studied the process cooling system serving a large plastic molding plant consisting of over fifty five injection molding machines [CHA 2002b]. The plant utilized 50ºF chilled water produced by a 260 ton water-cooled chilled water plant for all process cooling. The injection molding machines utilized cooling water for three basic load categories: hydraulic fluid cooling, "hot side" mold cooling, and "cold side" mold cooling. Of these three categories, relatively "warm" (85ºF) cooling water would have been adequate to meet the needs of the first two categories. This created an opportunity for energy savings by installing a cooling tower to provide "warm" water cooling to these loads for the 55+ injection molding machines.

To quantify the base case energy consumption attributable to injection molding line cooling, power consumption of the existing chiller compressors was monitored and recorded for a period of two weeks. From this data, manufacturer's chiller performance curves were derived and applied to compressor power profiles to obtain ton-hour consumption over the monitoring period. During this period, production data was also gathered. This data was used to determine the energy and ton-hour consumption per pound of product processed or unit cooling energy consumption (UCEC). Since production varies over a typical year, base year cooling energy was calculated by multiplying the calculated UCEC by base year annual production volume (lbs.). This method of calculating annual compressor energy consumption is considered valid since the chilled water plant is only operated for process loads and during production hours.

Key to the energy analysis was the calculation of a reasonable fraction of the total cooling load that should be assigned to both the "warm" and "cold" temperature loads since the displacement of "warm" loads onto a cooling tower system forms the basis of potential energy savings. Since each of the injection molding machines varies significantly in capacity, product being run, schedule, and cooling requirements, the most accurate method to achieve this would involve instrumenting each machine with both flow and temperature sensors for each of three cooling flow streams. Data collected over a monitoring period would permit the subsequent calculation of both high and low temperature load ratios that may be applied to the annual cooling energy consumption described earlier. Instrumentation of each system, however, in the above manner is impractical and costly and was therefore not pursued. Instead, load ratios were calculated using design heat load values that were quantified based on commonly accepted injection molding design guidelines and heat balance calculations that were based on actual spot measurements of average product material temperatures.

The analysis predicted a potential savings of over 900,000 kWh per year resulting in $66,000 annual cost savings. The project was implemented after which system performance was verified and actual savings slightly exceeded predictions. The project payback was approximately 1.4 years.

Innovative approaches to production efficiency. CHA recently assisted a large molder of plastic parts [CHA 2003a] in reducing production cycle times and thereby increasing net throughput with a small marginal increase in overall energy usage, which results in an overall reduction in energy use per production output. The project's success resulted from recognizing the importance of controlling temperatures within each mold cavity of a multiple-cavity, hot runner mold assembly. The project involved the following:

- Retooling the plant's mold bases to incorporate an insulating shell
- Incorporating independent spiral heaters to serve every mold nozzle within a multi-nozzle mold assembly
- Improving water cooling channels
- Embedding temperature sensors for each nozzle in the mold base
- Validating the concept by developing a transient heat transfer thermal model of the new mold assembly using finite element analysis (FEA) software

This project illustrates a critical concept often overlooked by energy managers and production engineers regarding energy efficiency in manufacturing operations: if production yield can be increased and cycle times reduced with a relatively low incremental energy investment, overall production energy efficiency is improved. In this project, additional benefits included reduced scrap and rework, and lower heat gain to air conditioned spaces.

Since the decision to move forward with implementation of this project represented a considerable capital investment, it was imperative to first quantify the concepts to the greatest degree possible. This was accomplished by developing a transient heat transfer model of a conventional mold base assembly using ALGOR™ finite element software. Once the model was created, it was "calibrated" to match the performance of an identical mold base installed on an operating injection molding machine. Test runs were performed on the machine using data loggers to record the electric resistance heater's current profiles, and similar data was collected on the mold base cooling water circuit. With this "real world" data, minor adjustments were made on the virtual mold base so that it behaved in a manner similar to the test unit.

Using thermal parameters obtained from the "calibrated" virtual mold base, the "next generation" mold base was modeled and used to predict the performance of the new assembly, and the performance of the two models was compared. With highly encouraging results predicted, the plant was prepared to invest capital in retooling. The predicted benefits of this project include:

- 85% reduction in production electric energy usage for direct electric resistance heating, space cooling and cooling water pumping energy resulting in 879,000 kWh and $70,000 per year saved
- 25% reduction in molding machine cycle time resulting in 1.6 million kWh and $990,000 per year saved
- 50% reduction in scrap rate resulting in 161,000 kWh and $99,000 per year saved

The above benefits do not include the ability of the plant to increase its overall production output and the resultant profits from increased sales. At the time of this writing, the plant is in the process of implementing the capital upgrades of this project which had a payback of less than 2 years. Verification of results is expected in 2006. NYSERDA provided an incentive under their Industrial Process & Productivity Improvement Program.

Food Processing Industry

Food processing operations are also highly energy intensive. Processing operations typically require heating and cooling during the manufacturing of food products; and refrigeration plants for storage of raw materials, work in process, and finished products. Opportunities exist for energy efficiency improvements at all levels including facility systems, process support utilities, and at OEM system level. Typical energy-intensive aspects common to food processing plants include:

- Process cooling
- Process heating
- Pasteurization
- Refrigeration
- Sterilization
- Product curing

Product Pasteurization

At a manufacturer of maple syrup, pasteurization was part of the production process [CHA 2003c]. The syrup was preheated with steam, pasteurized, and cooled for final product packaging. Heat generated during the pasteurization process was rejected and wasted. By adding a regenerator section (heat exchanger) to the pasteurization process, the process heat could be reclaimed from the post-pasteurized product and used to preheat the prepasteurized product, saving natural gas used for steam production and water/sewer charges as the result of single pass cooling of the post-pasteurized product. For a plant that produced 7 million gallons of maple syrup annually, 43,000 therms of natural gas and 9 million gallons of cooling water were saved, resulting in $62,000 per year in savings with a payback of 1.1 years.

Product Temperature Control

The process for a manufacturer of salad dressing products required the injection of temperature controlled soybean oil [CHA 2003c]. As a raw material, the soybean oil was stored in large silos and maintained at a temperature of 45ºF using a glycol chiller system. The energy consumed to maintain the soybean oil at that temperature was wasted, since the oil could be stored at ambient temperatures with no detrimental effects and lowered to the required injection temperature only when needed.

The potential opportunity identified was to utilize the plant’s large central ammonia refrigeration plant to chill the oil on-demand rather than maintaining the oil at refrigerated temperatures in storage. The reserve capacity of the ammonia plant was more than sufficient for this purpose.

To quantify the load profile for the base case system, the glycol chillers were instrumented for power consumption over a period of two weeks to establish the cooling energy required by the existing storage system. The proposed system consisted of a smaller glycol loop that was served by the central ammonia plant. The new glycol loop would chill the oil on-demand before mixing the oil as a key ingredient of the process line. Since production operations were primarily one shift per day, savings would be realized by eliminating the continuous heat gains of the large storage silos, along with some pumping energy attributable to the silo system. The new glycol loop pumping system would be substantially smaller.

By utilizing an existing central ammonia refrigeration system to chill the soybean oil on-demand, a plant that consumed 3 million gallons of soybean oil annually, saved 335,000 kWh annually with a payback of 1.0 year.

Facility Infrastructure Growth

As plants grow and change to meet production needs, such as new or renovated production lines, central process utilities are often expanded with inadequate consideration given to long range impacts. This often results in central utility systems that become plagued with capacity shortfalls, bottlenecks, and controllability issues, which contribute to efficiency degradation and wasted energy. Examples of these utilities include:

- Steam
- Chilled water
- Compressed air
- HVAC (particularly, process and general exhaust)

Process Chilled Water

At a large manufacturer of plastic packaging products, a 2,200 ton chilled water plant provides cooling primarily to process loads, but also provides limited comfort cooling during the summer months [CHA 2003b]. Over a 30 year period, the plant grew and evolved, and the chilled water system also expanded. Chillers and loads were added, and piping was added and extended. Pumps were changed out for larger units, and booster pumps located where cooling water flow was determined to be insufficient. At the time of the investigation, the plant was operating six chillers of various capacities located in different parts of the plant, but feeding a common network of distribution piping. Chilled water was being produced by operating chillers at 45ºF; however, the plant had difficulty achieving desired water temperatures in the distribution system due to piping anomalies discovered during the study, resulting in short-circuiting return water back to the system's supply header. The piping layout may have been appropriate when installed, but became an impediment as the plant's needs evolved. Understanding the flows within the piping network was extremely difficult. Multiple loops had been added to the network with hundreds of branch lines and cross-connections. Some areas of the plant experienced extremely insufficient chilled water flow, while other areas had an excess. In addition, reliable documentation of the piping distribution system did not exist. The energy impacts of these conditions were suspected to be considerable.

The first step taken was to perform a field survey of the entire system to document the piping network layout and pipe sizes. The distribution system could then be qualitatively studied; however, the system was so complex that a multi-nodal software package was required to simulate and solve the system flow condition. Pipe-Flo™ software was used to simulate the network.

Rather than attempt to document and predict the pressure drops through every end load and component in the system, the simulation was "calibrated" by taking approximately 50 flow readings at key locations within the network using a clamp-on ultrasonic flow meter. Through an iterative process, these readings were used to reconcile the flow model so that it behaved in a manner similar to the real system. With a reasonably accurate flow model, piping modifications were "tested" on the simulation to determine the effectiveness at solving the system's numerous anomalies. At the time of this writing, it is not known whether this approach has been tested by others in similar applications, however, by reconciling multiple (± 50) dependent flow nodes in the system to within approximately five to ten percent of actual readings, it was determined, based on engineering experience that the model was behaving in a manner that was "reasonably" accurate for its intended purpose. That purpose was to predict the effect of specific piping design modifications that would correct known deficiencies without causing unwanted side effects.

In parallel with the hydraulic modeling phase of this project, all chillers were instrumented and monitored for power consumption and temperatures for a period of two weeks. Since the system was constant flow, spot flow readings were taken. From this data, a baseline chilled water load was derived and extrapolated across the base year adjusting for production and weather effects in a spreadsheet bin model that was used to evaluate plant energy consumption. Annual electric consumption of this base chilled water system was determined to be over 7 million kWh.

This project illustrates that energy modeling alone would have been ineffective in diagnosing the root cause of this system's inefficiencies. The cause was due to short-circuiting of warm return water back to the chilled water supply header. The result was that the plant needed to produce chilled water that was approximately eight degrees colder than necessary to meet end-use needs had the piping anomalies not been causing these problems.

The approach was a success and enabled the plant to implement system upgrades at minimal capital cost which entailed only minor piping modifications. After solving the hydraulic problems, it was possible to incorporate other measures, including variable speed pumping, central chiller controls, and raising the leaving water temperature of all operating chillers. The project resulted in an annual energy savings of over 3 million kWh and $175,000 with a simple payback of 1.6 years. This does not include the anticipated production benefit of providing constant temperature and adequate flow to all process loads.

Compressed Air

At a large manufacturer of aluminum sheet, three manufacturing areas consumed an average of 6500 scfm of compressed air on a 24 hour, 7 day per week basis. The three areas had a common piping distribution system, but each area had its own compressor room. Four centrifugal and four reciprocating compressors were installed. As the plant restructured over time into three separate operating units, there was little control over the operation and use of the compressed air system. As equipment was added, piping was modified without consideration to the overall plant distribution system, and individual dryers were added throughout the plant instead of correcting dryer capacity issues.

The compressed air system was monitored for a 14 day period, including pressure at key locations throughout the plant, system flow, and compressor loading. Annual operating costs were determined to be $695,000 or $107 per scfm with electric consumption over 9 million kWh annually. Pressure fluctuations exceeded 20 psi, compressor controls were inadequate, two compressors had exceeded their useful lives, and approximately 2000 scfm of misapplications were identified. These misapplications included agitators and inefficient blow off nozzles and amplifiers.

Through reconfiguring and upgrading the storage, drying, and distribution system, in conjunction with an integrated control system and correction of misapplications, the plant could operate on six compressors. Electrical consumption could be reduced by 3 million kWh annually and, combined with maintenance savings, resulted in $380,000 savings annually with a payback of 3 years.

Process Heating and Cooling

Many industry sectors rely on process utilities to provide the energy necessary to produce products and control manufacturing processes. Throughput, cost, and quality of the products are given top priority, with energy usage secondary and sometimes considered uncontrollable. Most manufacturing processes rely on some form of process heating and/or cooling. This includes those already discussed, as well as paper and pulp, cement industry, pharmaceutical, machining, etc.

By defining and quantifying process parameters that produce a quality product, systems can be optimized and result in maximum throughput at an efficient use of energy.

Coating Dryers

A manufacturer of door gaskets/wire carriers for the automotive industry had a coating process that was cured and dried using electrically heated ovens [CHA 2000]. Due to the size, type, and capacity of the ovens, throughput was limited and operating costs high. An energy line balance model was developed based on coatings used, drying temperatures required, product properties, product throughput, and product mix. Total energy was calculated for product heating, drying air heating, evaporation heating, and convection and radiation losses. The existing drying system was compared to alternative technologies including RF, infrared, and hot air impingement.

To confirm that product quality, product throughput, and energy performance could be achieved, pilot testing was conducted of these technologies. Results from the testing indicated that gas fired hot air impingement technology would provide the most efficient solution, as follows:

- Capacity could be increased 50% on the existing production lines
- Energy consumption per 1000 ft. of production would reduce by 75%
- Energy usage savings of $60,000 annually
- Labor and overhead savings of $210,000
- Payback of 2.2 years, not including the ability of the plant to increase its overall production output and the resultant profits from increased sales

Cement Process Heating & Cooling

A manufacturer used constant speed fans totaling over 2100 HP with damper control for kiln furnaces and coolers for producing 640,000 tons of cement annually [CHA 2004a]. Annual electric consumption for these fans is over 10 million kWh. Power measurements and damper positions were recorded hourly for an eight day period with spot measurements for static pressure. Utilizing the measured data and fan curves, the savings for converting to variable speed drives were over 4 million kWh, resulting in $240,000 annual savings and a 1.8 year payback.

Machining Temperature Control

A manufacturer of high tolerance machined parts relied on grinder coolant to maintain temperatures and control of the machining process to meet critical tolerance specifications [CHA 2004b]. Inefficient cooling systems resulted in increased scrap rates on three of four grinders. To minimize scrap rates, line feed rates on these three machines were lowered to maintain acceptable levels of performance. Critical products were only set up on the one machine that had adequate cooling, resulting in the other machines being under utilized. Alternate coolants were also being utilized in the machines, one of which allowed higher feed rates and shorter machining times. To determine the cooling load requirements, a test was performed to measure grinder coolant temperature increase at a measured feed rate over an eight hour shift. This will vary according to material being machined, feed rate, and amount of material to be removed. This data and the plant's experience and production records were utilized to determine the average load over the year and develop a model for performance of each grinder with proper cooling.

By installing a central chiller system for the grinder coolant and standardizing on the preferred coolant, the following benefits could be achieved:

- Reduction in scrap rate of 5% resulting in $15,000 annual savings
- Throughput from the three machines could be increased 25% resulting in $47,000 additional machine capacity revenue annually
- 58% reduction in coolant cooling energy consumption per operating hour or 41,000 kWh annually
- Annual coolant related costs would reduce $12,000
- Elimination of heat rejected into air conditioned space
- 1.7 year payback

Conclusions

Based on the experience of the authors in identifying, quantifying, and implementing energy efficiency for industrial processes and process support operations needs, the methodology to achieve success should consider the following:

- There are few “canned” conservation strategies for industrial processes. Many processes are industry-unique.
- The analysis of industrial process energy efficiency is often contingent on fundamental engineering principles such as energy and mass balances to identify and quantify waste.
- The best results are based on actual field measurement of critical parameters such as flows, temperatures, pressures and power. Data logging is vital when processes incorporate variability over time.
- When seeking energy conservation opportunities that directly impact process operations, the concerns of the process engineers and process managers must be considered. In most industrial plants, product quality and production efficiency are priority. Energy conservation efforts must not override these metrics, and for energy efficiency projects to be successful, buy-in from the production group is critical.
- Energy efficiency measures should be tied into productivity improvements (i.e. yield, throughput)

Key aspects that can be identified and transferred to many industry sectors include the following:

- OEM supplied equipment is typically provided to minimize first time costs, not optimize energy efficiency
- Process utilities are used, added, or expanded to support process needs and are not always the most efficient method
- More efficient methods of control are available today then when processes were first installed

Many opportunities exist for achieving energy efficiency in industrial processes which will benefit companies in maintaining their competitiveness in a global environment.

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