Energy Efficiency in Pumping Systems: Experience and Trends in the Pulp & Paper Industry

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ABSTRACT

Approximately two-thirds of all US industrial electricity consumption is by electric motors. Pumping systems account for an estimated 27% of this electrical motor consumption. A recent study funded by the US Department of Energy estimates that optimizing the energy efficiency of these pumping systems could reduce consumption by over 20,000 GWh/year using existing, proven techniques and technologies. This study suggests that 22% of the pumping systems savings potential lies within the pulp and paper industry.

Energy use analysis being conducted by the US Department of Energy is leading to identification and quantification of savings opportunities within pulp and paper mills. Additionally, Lawrence Berkeley National Laboratory efforts over the past two years have involved extensive contact with the pulp and paper community on motor systems-related issues for the US Department of Energy's Motor Challenge program. This experience has provided an understanding of mill opportunities for improvement through contact with mill operating personnel throughout the United States.

This paper examines the applications of pumping systems in the pulp and paper industry, and identifies the most common energy optimization techniques implemented to date. Options such as adjustable speed drives, impeller trimming and multiple pumping arrangements are discussed.

Introduction

Approximately two-thirds of all US industrial electricity consumption is by electric motors. Pumping systems account for an estimated 27% of this electrical motor consumption. Within the pulp and paper industry, pumping systems account for over 31% of the motor system energy consumption (DOE 1998). A recent study funded by the US Department of Energy estimates that optimizing the energy efficiency of industrial pumping systems could reduce consumption by over 20,000 GWh/year using existing, proven techniques and technologies (DOE 1998). This study suggests that over 6,000 GWh/year, or 22%, of the pumping systems savings potential lies within the pulp and paper industry, with pumping systems optimization having the highest energy savings potential of all motor systems (see Figure 1). Figure 1 compares major motor system categories within motor horsepower ranges, and shows the pumping system opportunities clustered in the higher horsepower ranges. The study went on to identify the installation of speed control in place of throttling and bypass control valve mechanisms as the greatest single opportunity for cost-effective pumping system energy savings within the pulp and paper industry.

This paper will discuss the types of pumps predominant in the pulp and paper industry, and their typical applications. The opportunities for energy savings and life cycle cost improvements for the major pumping system applications will then be evaluated.

The author's activities with the pulp and paper industry are a part of the Motor Challenge program within the US Department of Energy's Office of Industrial Technologies. Motor Challenge seeks to improve US industrial efficiency through use of the "systems approach" for motor system design and analysis. This effort supports the industry's Agenda 2020 energy research initiatives by providing near-term opportunities for energy and cost savings using existing technology and methodologies.

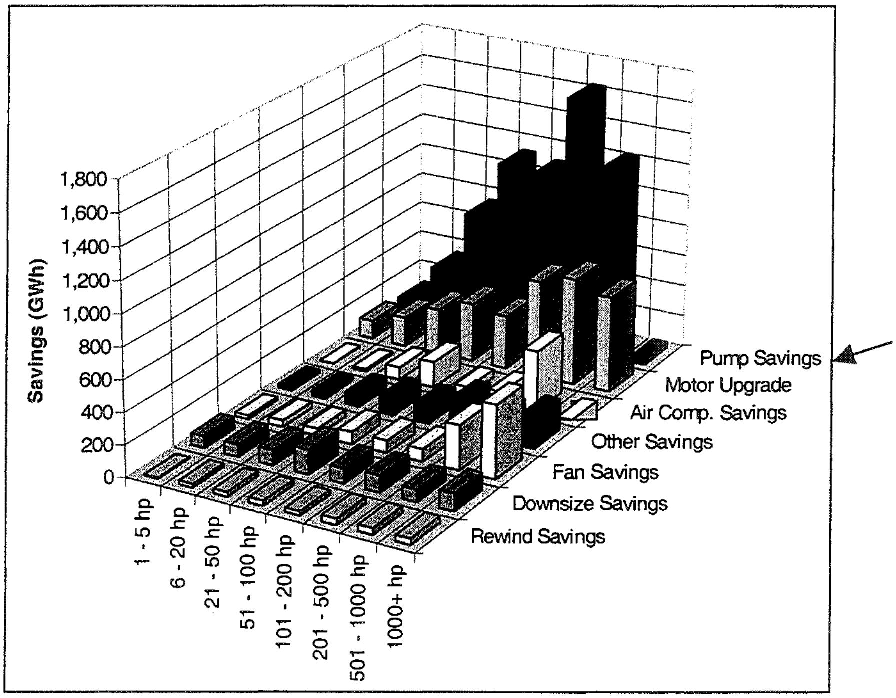

Figure 1. Potential Energy Savings by Application and Motor Size for Paper and Allied Products (SIC 26) (DOE 1998)

Pumps and Pumping Systems Used in the Pulp & Paper Industry

Pumps are generally classified into two main groups -- dynamic or positive displacement pumps. Dynamic pumps impart kinetic energy to a fluid, which is converted to pressure as the fluid leaves the pump impeller. Positive displacement pumps pressurize a fluid by displacing a fixed volume with each piston stroke or shaft rotation, and include reciprocating displacement pumps such as piston types, and rotary displacement pumps such as gear, rotary lobe, and screw designs. Positive displacement pumps are usually preferred for viscous or abrasive liquids and liquids requiring metered or precisely controlled delivery.

Each of the many designs within each group has advantages and disadvantages that dictate the selection of one design over the others for a given application. Within the pulp and paper industry, dynamic pumps are typically recommended for applications involving high volumes or liquids mixed with large solids or stringy fibers, such as paper stock.

Centrifugal pumps, the most common type of dynamic pump, are predominant in the pulp and paper industry. Centrifugal pump categories include axial (propeller), mixed flow, and radial pumps. Each has many variations in design, but their general characteristics include low maintenance, long operating lives, and safe operation.

A pump is but one component of a pumping system. To create a system with optimal efficiency and minimal life cycle cost, one must consider the operation of the entire system and the interactions of each component with other components. The other components in a typical system include the prime mover (usually an electric motor), piping, valves, and end-use equipment.

Pumping systems are generally classified as closed-loop or open-loop systems, both of which are common in the pulp and paper industry. A closed-loop system recirculates fluid through its piping and other components. An open-loop system has an input and an output, as fluid is transferred from a fluid source to a process or storage container. Closed-loop systems typically have no static head loads, so frictional losses constitute their dominant pump load. In contrast, open-loop systems typically have static head requirements due to elevation and tank pressurization needs. As discussed later in this paper, energy and life cycle optimization strategies will differ significantly for these two systems, especially if variable frequency drives are employed.

Pumping systems have a large variety of applications in the pulp and paper industry, including steam and condensate pumps, chemical pumps, and various types of hydraulic and lubrication pumps. Several of the specialized pulp and paper applications are described in the following paragraphs. All of these demanding applications require special care in the design of the pumping system and equipment selection. For example, abrasive media may make a pump susceptible to internal recirculation (leading to excessive wear) if the discharge chamber is oversized. Individuals considering energy efficiency improvements to pumping systems must be mindful of these special design requirements, since compromises to the reliability and durability of the systems cannot be tolerated.

Properly functioning fan pumps (which supply stock to the paper machine head box) are essential to paper quality due to their role in supplying an even flow of paper stock to the paper machines. Fan pumps are usually double suction (impellers with dual, opposed inlets with a common outlet) pumps with split, staggered vanes. Fan pumps and other pumps used for paper stock pumping must meet particular suction conditions for proper operation, based on the consistency of the paper stock, fiber length, degree of agitation, and entrained air (Coan 1995). Broke service pumps are another special type of paper stock pump. These pumps spend much of their operating hours in standby mode handling a low flow. At the time of a paper web break, these pumps must rapidly remove the broke (partly manufactured paper from a broken web or from trim on a paper machine) to a broke storage area for reprocessing (Coan 1995). Two-pump systems are used at many mills to handle these variations in flow.

Centrifugal cleaner pumps are subjected to very abrasive operating conditions, such as sand and other debris. Shower pumps (which provide water sprays to clean fibers and contaminants from felt, wire, rolls, and other paper machine components) must operate at high speeds and pressures. Multi-stage or multiple pumps in series are common in shower pump applications. Pumps used in coating applications must handle high viscosity liquids with up to 70% solids. Such applications require increasing the internal clearances in the pump casing, leading to the need to oversize impellers and motors to compensate for the pump's loss of efficiency (DOE 1999).

Black liquor (a complex mixture of inorganic elements and degraded wood substances) pumping requires pumps with special stuffing box (the point where the shaft penetrates the pump casing) packing or mechanical seals (seals using springs or bellows) to handle the pressures, temperatures, and abrasiveness found in black liquor systems. Green liquor, white liquor, and lime mud (all products of the chemical pulping process) present abrasive environments for pumps. Pumps used in bleach plants are exposed to a corrosive environment from chemicals such as chlorine dioxide, calcium, and sodium hypochlorite. This requires special materials, such as 317 stainless steel or titanium. Digester (equipment which processes the wood chips into pulp) recirculation pumps are exposed to large temperature and pressure swings because digestion is a batch process. High temperatures and pressures are present during the batch service, and then cool-down is experienced between batches. Special packing or seals are usually required, and allowances should be made for thermal expansion of the piping.

The Systems Approach

Evaluating the pumping system as a whole, rather than a collection of individual pieces of equipment, is necessary to provide cost-effective operation and maintenance of that system. This "systems approach" looks at both the supply and demand sides of the system and how they interact. The systems approach usually involves the following types of interrelated actions (DOE 1999):

- Establishing current conditions and operating parameters;
- Determining present and estimating future process production needs;
- Gathering and analyzing operating data and developing load duty cycles;
- Assessing alternative system designs and improvements, including estimates of the capital and life cycle costs of the alternatives;
- Determining the most technically and economically sound options, taking into consideration all of the subsystems using a life cycle cost analysis;
- Implementing the best option;
- Assessing energy consumption with respect to performance;
- Continuing to monitor and optimize the system; and
- Continuing to operate and maintain the system for peak performance.

Energy Saving Strategies

Whether evaluating a new or upgrading an existing system, each pumping system installation in a pulp and paper mill will have certain unique characteristics, and therefore must be evaluated individually for energy efficiency improvements using the systems approach discussed in the preceding section. Equipment selection, specification, and system operation all provide opportunities for energy savings.

Equipment Selection

The efficiency of any pump is influenced by hydraulic effects, mechanical losses, and internal leakage. Pump users should be aware that manufacturers have many ways to improve pump efficiencies. For example, the pump surface finish can be made smoother by polishing to reduce hydraulic losses, but the additional first cost must be weighed against the energy savings. The efficiency of a pump is defined as the ratio of fluid power divided by the shaft input power:

$$\eta_p = \frac{P_f}{P_s}$$

where fluid power is proportional to the product of the volumetric flow rate, the head (pressure), and the fluid specific weight:

$$P_f = QH\gamma$$

and shaft input power is the product of the rotational speed and torque:

$$P_s = \omega T$$

Another common term is the wire-to-water efficiency, which is a measure of the combined motor and pump efficiency:

$$\eta_{ww} = \frac{P_f}{P_e} = \frac{QH\gamma}{P_e}$$

A term useful in application of the systems approach is system efficiency, defined as the efficiency of the pump, motor, and the distribution system:

$$\eta_{sys} = \frac{P_f}{P_e} = \frac{QH_s\gamma}{P_e}$$

The system efficiency simply compares the power output of a system to the power input. The equations above use the following nomenclature:

H = total head
H_s = static head
Q = volumetric flow rate
P_e = motor input power
P_f = fluid power
P_s = shaft power
T = torque
η_p = pump efficiency
η_{sys} = overall system efficiency
η_{ww} = wire-to-water efficiency
ω = rotational speed
γ = fluid specific weight

One straightforward way to increase the efficiency of a pump system by two to five percentage points is to install a higher efficiency motor. The national Energy Policy Act imposed a minimum efficiency on most general-purpose induction motors sold in the US, effective in October 1997. Motors formerly referred to as "standard efficiency" are no longer sold, and motors generally referred to as "high efficiency" motors are the standard product line available from motor manufacturers. Most manufacturers offer a more efficient model line, often referred to as "premium efficiency" motors, available at an incremental cost. For systems with high annual operating hours, as is typical in pulp and paper mills, an economic analysis will often prove that the reduced life cycle costs will justify this initial investment in a premium efficiency motor.

A recent study (DOE 1998) found that only eleven percent of US industrial facilities use written specifications when purchasing a motor, and only two-thirds of those facilities address motor efficiency in their specifications. About 28% of the recent motor purchases in the pulp and paper industry have been energy-efficient, but almost one-half of the mills surveyed had no energy-efficient motors among their motor purchases in the preceding two years.

Motor replacement also offers the opportunity to re-evaluate the system loads. Most facilities simply replace a failed motor with a new motor of equal horsepower, however, approximately 40% of motors in use in industry today are operating at less than 40 percent part load. This presents a good opportunity for "downsizing" – replacing the failed motor with a smaller horsepower motor.

The use of variable frequency drives (VFDs) in mills has increased dramatically in the past few years as a means of reducing energy consumption and demand through speed control. Applications for VFDs will be discussed in a later section, along with several other strategies and techniques that are often economically viable.

Pump Specification

Pump specifiers and purchasers are often overly conservative when specifying and selecting pumps. Hallock and Day estimate that over-specifying the flow requirements results in most pulp and paper applications having pumps operating at only 60 to 70% of their BEP (Hallock and Day 1982). Similarly, most pumps in the pulp and paper industry are consuming 10 to 30% more energy than necessary because of excessive throttling brought on by over-specifying pump pressure requirements. Often, a pump is specified for planned future production increases, resulting in the same inefficiencies as being overly conservative. An economic evaluation should be considered in these situations, comparing the costs of inefficiency to the initial cost of a smaller pump, or a multiple pump arrangement.

System Operation

The operating condition where a pump has its highest efficiency is referred to as the Best Efficiency Point (BEP). This is best described graphically, as shown in Figure 2, which is the performance curve for a typical centrifugal pump. The performance curve represents the pressure generated by a pump over a range of flow rates, and will vary for each pump model and size. Manufacturers typically provide pump performance curves in their sales literature. Figure 2 also shows the shaft input power in terms of brake horsepower (BHP), plotted with respect to flow rate.

The BEP is the point at which the pump operates most cost-effectively in terms of both energy efficiency and maintenance considerations. For example, operating at a flow rate above the BEP could lead to excessive vibration, noise, and erosion. Operating at reduced flow rates could result in liquid temperature buildup, excessive radial thrust, and recirculation at the impeller suction or discharge (Hydraulic Institute 1994). Thus, operation near the BEP minimizes wear to seals, bearings and other parts. In practice, operators are not able to control a pump consistently at its BEP due to changing demands, but maintaining operation within a

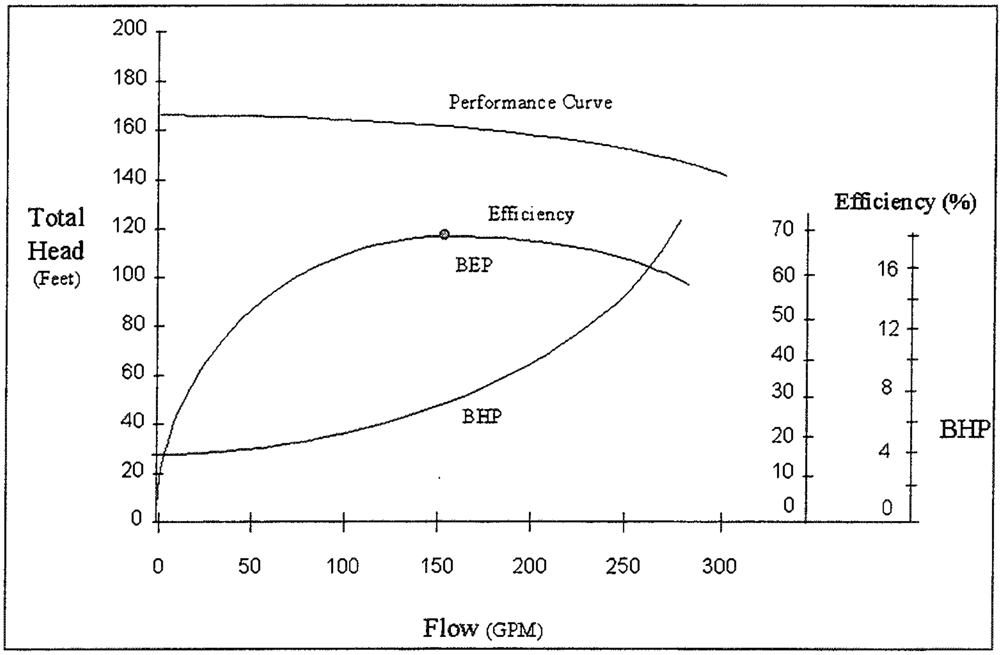

Figure 2. Centrifugal Pump Performance Curve (DOE 1999)

reasonable range of the BEP will lower overall system operating costs (DOE 1999).

Many pumps in operation today are oversized for their applications due to either overly conservative designs or reductions in the system loads. One opportunity for energy reduction in such systems is impeller trimming (see Figure 3). Impeller trimming is the process of machining down the diameter of an impeller. The resulting smaller impeller reduces the tip speed, thereby reducing the flow and pressure generated by the pump. A pump user should consider trimming if the system being evaluated is creating high noise or vibration levels, indicating excessive flow through the pump; or system bypass valves are open, indicating excess flow available to the system. In addition to energy savings, impeller trimming can reduce maintenance costs through reduced vibration, and reduced wear on piping, valves, and piping supports. Further detail on impeller trimming and other optimization strategies can be found in the US Department of Energy Publication, Improving Pumping System Performance: A Sourcebook for Industry.

Another energy-efficient retrofit opportunity, especially for paper stock pumps, is to replace the pump "stock" impellers with "process" impellers. The stock impellers have fewer vanes than the optimum number, a design meant to enhance reliability. However, many stock pumps do not require the less efficient impeller to have high reliability.

The pumping distribution system can offer significant opportunities for efficiency improvements. Larger pipe sizes create less friction for a given flow rate than smaller pipe sizes. The reduced friction loss reduces the pressure requirements, but the larger pipe size incurs an extra initial equipment cost. Proper piping design will also minimize sharp elbows and transitions. To maximize efficiency, piping configurations must allow the pumped fluid to develop a uniform velocity profile upstream of the pump inlet. This is ideally achieved by a straight length of pipe, or a long radius elbow if space constraints exist.

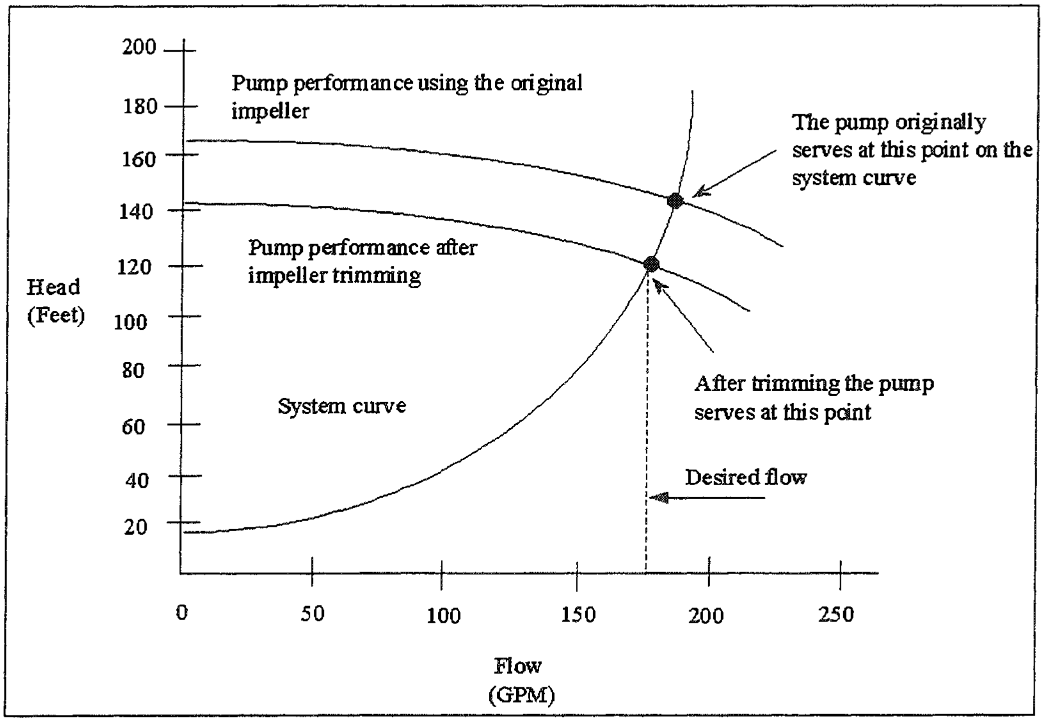

Figure 3. The Effect of Impeller Trimming on Pump Performance (DOE 1999)

Variable load applications. Pumping applications with loads that vary over their duty cycle are usually candidates for energy efficiency optimization. Adjustable speed drives and multiple pump arrangements are usually much more efficient than bypass lines or throttling valves.

The most common type of adjustable speed drive is the variable frequency drive (VFD). VFDs adjust the electrical frequency of the power supplied to a motor to change its rotational speed. Whether or not a VFD is appropriate depends upon the pump performance and system head curves, as explained below. Properly applied, VFDs save energy and lengthen the useful life of the pumping system.

Slowing a pump's speed will reduce the system pressure and flow, and therefore the brake horsepower is reduced and the pump efficiency curve will shift to the left (see Figure 4). More important in most applications, however, are the savings resulting from reduced frictional and/or bypass flow losses. In pumping systems that are primarily frictional (such as closed-loop circulating) systems, the pump affinity laws provide a good indication of the savings potential of varying the pump speed. The affinity laws provide that the flow rate is proportional to the pump speed, the pressure is proportional to the square of the speed, and the shaft power is proportional to the cube of the pump speed. For example, a 20% reduction in pump speed will reduce the flow rate by 20%, but the power consumption will decrease by almost 50%.

However, when there is static head (such as with elevated tanks), the system pressure variation no longer follows the affinity laws because the static head remains constant as the frictional head varies. For this reason, VFDs can cause problems in applications with high static head. The slower speeds can induce vibrations, shaft deflection, or high bearing loads similar to operating a pump at or near its shutoff head conditions. Therefore, to properly apply an adjustable speed drive requires careful analysis of the interdependence between the pump and the system. (Casada 1999)

In addition to the problems at low speeds mentioned above, VFDs may not be appropriate

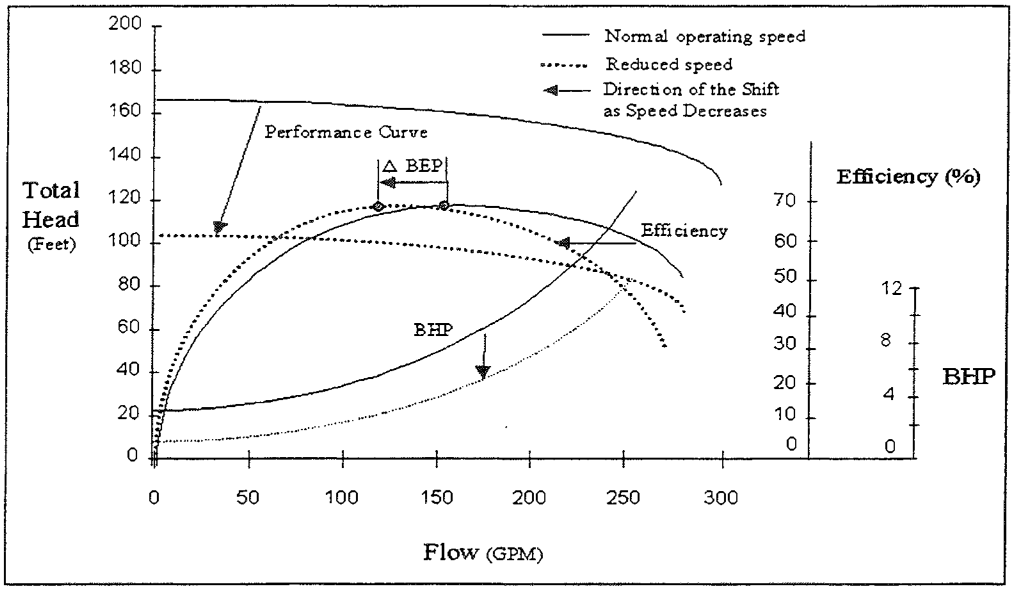

Figure 4. Effect of Speed Reduction on Pump Operating Characteristics (DOE 1999)

for all systems. For example, VFDs do not transmit energy at 100% efficiency; 95% efficiency is typical. Also, the harmonics created by VFDs have been known to affect some electrical systems.

VFDs can often reduce a systems life cycle cost by lowering system maintenance and repair costs. As speed decreases, bearing loads are decreased and shaft deflection is lessened. Pipes and piping supports also are subjected to fewer stresses. Also, the soft start capability of a VFD reduces wear on the pump motor and motor controller.

Black liquor pumps are often candidates for variable speed drives because the black liquor viscosity can vary significantly with relatively minor variation in temperature, thus altering the pressure requirements and pump performance. Variable speed drives are common replacements for throttling valves in fan pumps. In addition to the energy efficiency gains, the variable speed drives offer more precise control and do not transmit the undesirable pressure pulsations typical of throttling valves.

Multiple pump arrangements. In some pumping systems, especially those with high static head requirements, multiple pumps can be operated independently to meet demand changes. This allows each pump to operate more efficiently, improving the overall system efficiency. Multiple pump arrangements also can be used to provide flexibility, redundancy, and an ability to efficiently meet changing system flow needs. Occasionally a pump will serve two functions – recirculating fluid in a storage tank (low head, high volume), while at the same time providing a high-head, low-volume withdrawal. A design using two pumps could reduce the system energy consumption in this instance.

Typically, multiple pumps will all be of the same size and model and will be placed in parallel. Using different pump sizes poses risks from having the largest pump dominate the system and causing the other pumps to operate below their minimum flow ratings. Multi-speed pumps are another option that provides advantages similar to multiple pumps. Systems analysis should include a comparison of the capital costs (and space considerations) of multiple pumps with the energy savings over the life cycle of the equipment.

Life Cycle Considerations

The energy savings potential for pumping systems within the pulp and paper industry is estimated at over 6,000 GWh/year, yet capital expenditures for pumping-related energy efficiency improvement projects are minimal. Many pumping systems in pulp and paper operate around the clock, meaning that any additional initial cost premiums on improved efficiency or reliability can often be recouped in one year or less through reduced energy costs. However, new system purchase decisions and existing system retrofit decisions are usually based upon first costs.

Reduced energy consumption is low priority for mill management and engineering staff, whose interests in pumping systems center around performance and reliability. Energy efficiency improvements in the industry would be more commonplace if a thorough economic analysis was performed for system design and retrofit alternatives, focusing on life cycle costs. The potential pumping system and other motor system energy efficiency savings is equal to 5% of the operating margins within the pulp and paper industry (DOE 1998). Energy cost savings potential for a typical mill are in the range of $200,000 to $250,000 for pumping systems alone.

To best quantify and justify system improvements, mill personnel must undertake an analysis of not just energy savings, but also the maintenance savings and other system costs (environmental costs, disposal costs, etc.) over the expected lifetime of the system. Though life cycle cost analysis is proven and mature, it is not currently widely used as a decision-making tool for motor-driven systems such as pumping systems in the pulp and paper industry. Members of the Hydraulic Institute (a trade association of US pump manufacturers), in conjunction with EUROPUMP (a European trade association), hope to alter the decision-making process used by pump users. These two associations are currently working together to develop a Life Cycle Cost Document that will include a methodology to assist pump users in estimating and comparing alternative life cycle costs of ownership for pumping systems. This document and other tools under development are intended to be resources for industrial users of pumping systems, and are expected to be available by mid-2000.

Conclusion

Significant opportunities exist to improve the energy efficiency and reduce the life cycle costs of pumping systems in the pulp and paper industry using existing technologies and proven practices. Savings can be optimized by taking a systems approach, which considers the entire process system and the interactions of individual components on other components and on the system. Pulp and paper mills typically have hundreds of pumping systems, with many specialized pump applications. Energy savings opportunities exist through evaluation of each pumping system for operational improvements and careful equipment specification and selection, in particular proper sizing of pumps and piping. Impeller trimming for existing pumps can often make an oversized pump operate more efficiently. Adjustable speed drives can produce significant energy and reliability savings in pulp and paper pumping systems, and variable frequency drives in particular can be used successfully. Better documentation of the energy, maintenance, and reliability savings through life cycle cost analysis can often provide economic justification for energy efficiency improvements.

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