Progress in energy efficiency in fluid handling systems

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Abstract

Efficient Energy Use (EFEU) program was founded in 2011 to assess industry-level problems in energy efficiency in Finland. The current focus is in improving fluid handling systems with systems-level approach through pump control and also by developing next-generation equipment, such as pumps, agitators and pulpers for the paper industry. An important aspect of EFEU program is the co-operation between universities and equipment manufacturers to realize new systems-level results instead of just focusing on individual devices. As an example of research work in EFEU, this paper focuses on three research topics.

Variable-speed drives (VSD) have been identified to have one of the greatest potential for energy savings in various fields of industry as they allow energy efficient operation of fluid handling systems. As an example process, we present the pumping of a given amount of fluid between two tanks with the minimum energy consumption and fixed time. This process can also be a part of a larger system with in- and outflow from either tanks. The optimal control law for the pump rotational speed can be easily implemented in programmable VSDs.

Another case aims to assess the efficiency improvement potential in electric motors. We review the best available current technology and point out some weaknesses. We evaluate different future technologies according their cost and reliability and present our view of an ideal future motor for pump applications.

Finally, we present a case study from forest industry. In pulping process bales of pulp are broken down and mixed to produce a homogeneous water-fibre suspension. The rotor, which is responsible for breaking down bales, mixing the suspension, and cleaning the screen, has been redesigned based on CFD-simulations. We demonstrate considerable energy savings in this application.

These cases summarize the goals, results and also the future of EFEU project. Our new results provide control engineers appropriate tools to operate and control their processes and demonstrate considerable reduction in energy consumption in pulping process. The newly developed methods and equipment are set against the old ones to demonstrate the increased efficiency in each case.

Introduction

Fluid handling systems including pumps, fans and different kind of mixers are the most common end-use application for electric motors, making them a notable contributor to the global energy consumption [1]. As an example, single paper mill is operated with hundreds of electric motors driving pumps, fans, mixers, agitators and different kinds of conveyors with each one having power consumption in the range of tens to hundreds kilowatts (see Fig. 1). Operating costs are the single most important source of costs in fluid handling systems. Because of the high energy demand of fluid handling systems, small improvements in efficiency can lead to significant reduction of the life cycle costs [2]. Especially energy intensive equipment is found in forest industry for example in refining and pulping processes and in pumping of fiber suspensions.

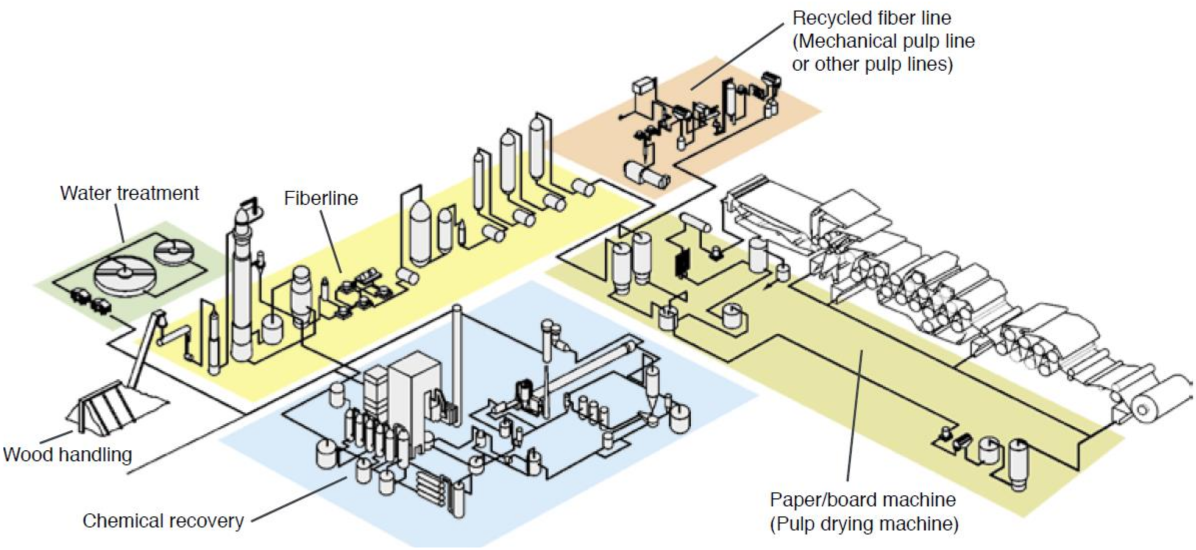

Fig. 1. End-use applications for electric motors in a paper mill [3].

Improvement of system component efficiencies and their variable-speed operation are key factors in energy efficient operation of systems, as the improved component efficiency should not be wasted by inefficient control method [4]−[5]. This kind of systems approach is one of the main ideas behind Efficient Energy Use (EFEU) program founded in 2011, which provides solutions for industry-level problems in energy efficiency in Finland [6]. Since its starting, EFEU project has provided means to design next-generation equipment, such as pumps, agitators and pulpers and to control fluid handling systems as energy efficiently as possible with the help of a variable-speed drive [7]. The conducted work is supported by the co-operation between universities and equipment manufacturers to realize new systems-level results instead of just focusing on individual devices, which is an important aspect of EFEU program.

The object of this paper is to introduce research results obtained in EFEU research program on three separate research topics (control of fluid handling systems; efficiency improvement potential in electric motors; efficiency improvements in pulpers). Since the research program is studying both the system components and their overall control, each case introduced in this paper is summarized with their expected energy savings potential. When possible, the effect of component efficiency improvement potential on total system energy efficiency is also analyzed with the concept of specific energy consumption E_s (kWh/m^3). Figure 2 shows how the improvement effect of component efficiency on the system E_s will gradually get lower, when the component efficiency is improved. For this reason, the focus of EFEU research program is set to the systems level and to the flow devices and their motors, which have the largest efficiency improvement potential available.

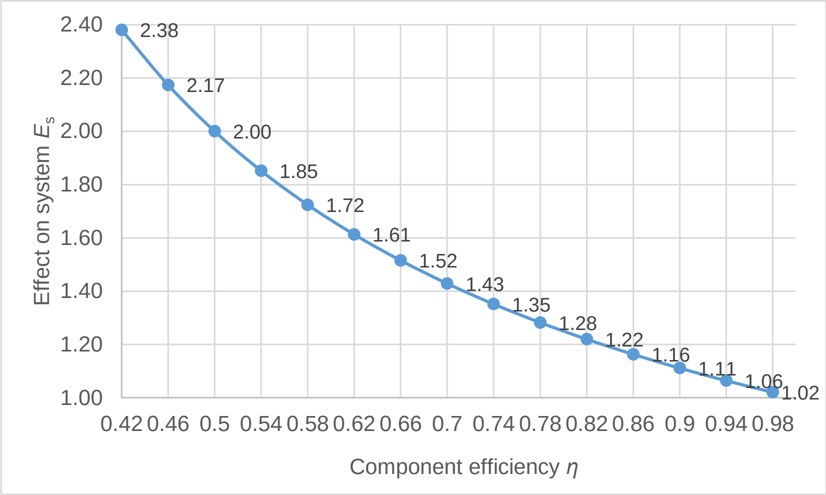

Fig. 2. Relative magnitude of system E_s as a function component efficiency η [4].

Energy efficiency improvement potential in electric motors

Fluid handling systems are most often operated with asynchronous induction motor (IM) which can be considered as the workhorse machine for the paper industry. Simple and mature construction of the induction motor combined with a rotor having short-circuited copper or aluminium bars makes this motor type cost-efficient and reliable. IM can also be driven with any frequency converter and it generally has good overall efficiency characteristics over the whole speed range, which is why the IM has been preferred option for driving a fluid handling system. Depending on their age and other selection criteria, induction motors currently operating in fluid handling systems mostly follow the IE efficiency classification in levels IE1 (previously known as EFF2 in Europe) and IE2 (previously known as EFF1). For a four-pole (1500 rpm), 15 kW motor these classes mean minimum efficiencies of 88.7 and 90.6 percent [8], see Fig. 3.

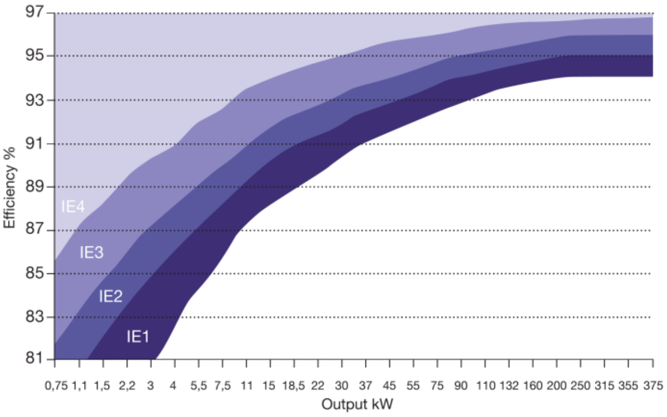

Fig. 3. International efficiency classes given for four-pole electric motors according to IEC standards IEC/EN 60034-30:2008 and IEC/TS 60034-31 [8].

Since the induction motor is neither the most efficient nor the most compact motor technology available nowadays [9], it gives room for the energy efficiency improvement in electric motors. Modern circulator pumps are a good example of energy efficient and integrated pumping systems, where permanent magnet synchronous motor (PMSM) is applied as the default motor technology. Compared to IM, permanent magnet motors have better power density due to the magnets in the rotor, so they can reach higher operating efficiency with more compact dimensions. As a practical example, first commercial PMSMs with IE5 level have been introduced in 2014 [10]. For the 15 kW four-pole motor, this would mean the minimum efficiency of over 94.3%.

Another higher-efficiency alternative for IM is the synchronous reluctance motor (SynRM) that can be considered as a combination of IM and PMSM. The advantage of basic SynRM is that it is cheap to manufacture as it only needs iron and copper. They are also available in IE4 efficiency level, meaning 93.9% motor efficiency with a VSD supply according to [11]. As downsides, SynRM requires a variable-speed drive for its operation and it has a small torque density and poor power factor which can be, however, improved by placing magnets in the flux barriers. Then, the machine is called PM-assisted SynRM (PMASynRM), which are also able to reach IE5 efficiency class in the power range of 1-15 kW [12].

When the above motor efficiency values are compared to E_s values shown in Fig. 2, one can see the relative E_s improvement potential to be around 0.1 units when the component efficiency is improved from 88% to 94%. A more detailed analysis on the energy saving potential with the motor efficiency improvement from IE3 to IE4 level was carried out in [13] for IE3 IM, IE4 SynRM and nearly IE5 PMSM by analyzing their measured efficiency maps. Results shown in Fig. 4 also illustrate the resulting pump operating points, when a Sulzer APP 31-100 centrifugal pump (1460 rpm, 47.5 l/s, 21.7 m and 12.9 kW as nominal operating values) was operated according to the standardized load profile for closed loop systems [10]. When efficiency maps are compared with each other, the efficiency benefit of PMSM seems clear with the motor efficiency of and over 92%. At all operating points, the motor efficiency improves with a graduation from IM to SynRM and from SynRM to PMSM.

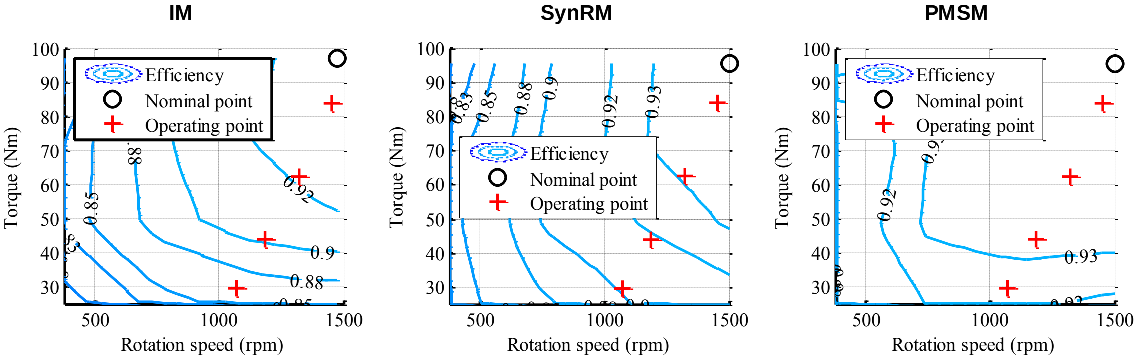

Fig. 4. The resulting pump operating points, when it is driven with an IM, SynRM and PMSM according to the load profile for closed loop systems.

The study was summarized by calculating annual energy consumption for the motor alternatives, which are given in Table 1. Compared with induction motor, the energy saving potential of SynRM and PMSM are in the range of 2 to 4%, as the studied motors have at least IE3 efficiency classification. When these values are converted to financial savings with 0.1 €/kWh electricity price, the resulting annual savings with the use of PMSM are around 200 € per single pumping system.

Table I. Energy consumption of the different motor types for the closed and open loop system loading profiles according to [13].

	IM	SynRM	PMSM
Closed loop system			
Annual energy consumption	54 987 kWh	53 659 kWh	52 886 kWh
Energy consumption compared with IM	100 %	97.8 %	96.4 %
Open loop system			
Annual energy consumption	58 771 kWh	57 521 kWh	56 779 kWh
Energy consumption compared with IM	100 %	98.0 %	95.8 %

If the comparison would have been carried out with IE1 or lower efficiency IM, the improvement potential would have been larger. Nevertheless, energy savings obtained with improved motor efficiency are clearly lower compared to the measured energy savings obtained with improved control of the system or with improved efficiency of the pump or pulper rotor.

Energy efficiency optimizing control methods

In reservoir pumping applications, for example in the process of Fig. 5a and in sewage pumping [14], a given amount of fluid is pumped from one reservoir to another. When the process time is flexible, the pumping process can be optimized quite freely with respect to the specific energy consumption, $E_s = E/V$, where E is the energy consumption and V is the total volume of fluid. A sensorless method to realize this E_s-based operation was described in [15]. In sensorless control, the operational point is determined based on the information retrieved from the VSD system and the estimate can be refined by combining the information from both VSD and system measurements [16].

Often the optimal pump control is limited by certain practical constraints such as a time limit and minimum and maximum flow rates recommended by the pump manufacturer. The energy-efficiency-based control of reservoir filling in [15] is also possible with time constraints as explained in [17]. An example is given below.

The energy consumption (E) and time (T) of a reservoir filling process can be defined as the following integrals:

$$E = \int_0^t E_\mathrm{s} \mathrm{d}V \qquad (1)$$

$$T = \int_0^t Q^{-1} \mathrm{d}V \qquad (2)$$

where Q is the flow rate (m3/s). During filling the tank in the process in Fig. 5a, the surface levels in the tanks change and the pump rotational speed must be constantly controlled so that E_s is minimal. However, when the time limit $T=T_0$ is imposed, the optimal operation cannot be found by a simple minimization procedure. By following the principles of the Calculus of variations, the following optimal control law can be derived for the rotational speed [17]:

$$\frac{dE_s}{dn} = C \frac{dQ^{-1}}{dn} \qquad (3)$$

where C is a constant which depends on the process time limit. Equation (3) is applied as follows: the rotational speed is constantly changed in small steps dn and the changes dE_s and dQ^{-1} are monitored. Rotational speed is controlled such that Eq. (3) is satisfied. Few process runs are needed to find the correct value of C which corresponds to the desired process time.

As an example of the new control procedure, consider a process where a A_2=20 m^2 tank is filled with 240 m^3 of water. The initial and final static heads are $H_{s,init}$=2 m and $H_{s,final}$=14 m and the system curve is $H=H_s+9000Q^2$. The pump characteristics are shown in Fig. 5b. When we ignore the time limit and control according to the minimum specific energy, this process consumes 42.9 MJ energy and requires 11168 s to complete. However, with a time limit of T=9000 s, the process energy consumption is 45.7 MJ. Thus the process time can be reduced considerable with only a small increase in energy consumption. The optimal flow rate and head is shown in Fig. 6.

Energy saving potential of optimized control greatly depends on the surrounding system and set process requirements. Compared with constant speed operation of pumps at their nominal speed, optimization methods are able to decrease system energy consumption even by 30…40 %. Also compared to the use of best constant rotational speed for the reservoir emptying (or filling), which also requires the use of VSD, the method proposed in [7] for identifying the optimum speed profile could further decrease the energy consumption by some percentage units. Compared with energy savings potential in motor efficiency, these results underline the importance of good control for a fluid handling system.

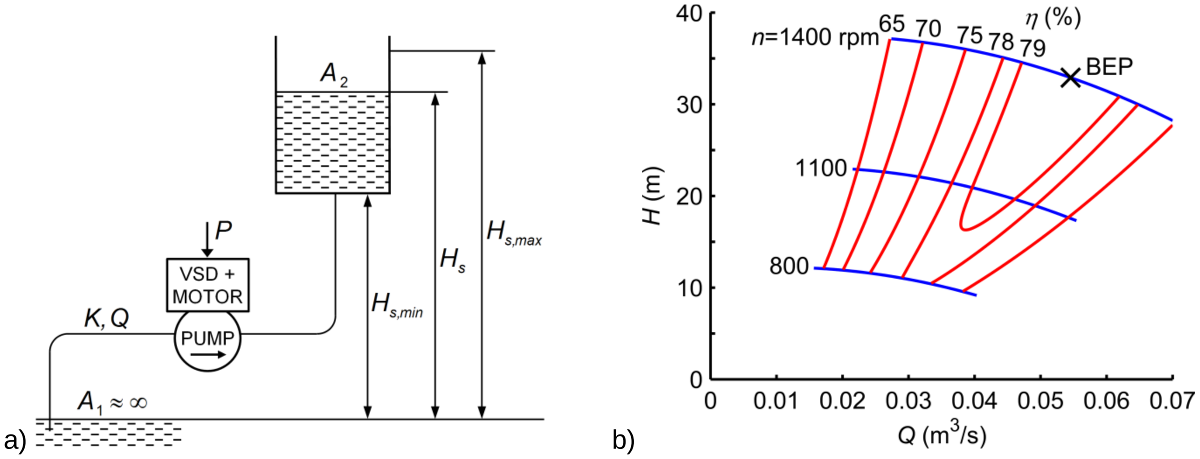

Fig. 5. Process layout (a) and pump characteristics (b) in the example.

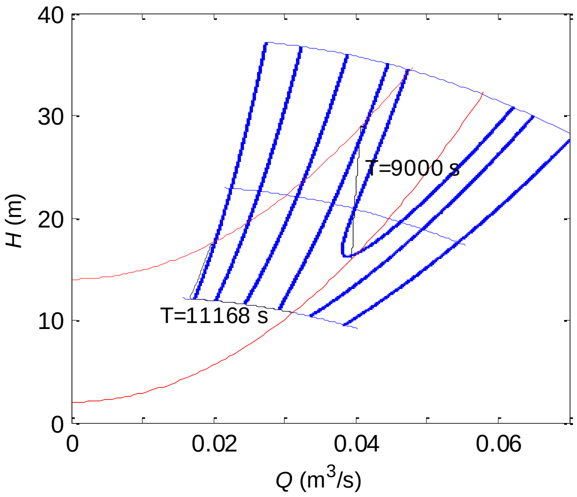

Fig. 6. Optimal operation in reservoir filling.

Energy efficiency improvements in pulpers

With reference to Fig. 1, in *Pulping process*, dry bales of pulp are mixed with water to produce a homogeneous water-fiber suspension. Bales are dropped into water filled tank, which is agitated by the rotor located at the bottom of the tank. The rotor is shown in Fig. 7. The process can run either in batch wise or in continuous mode. In batch operation bales of 250 kg are fed to the pulper, and process is run until the suspension becomes homogeneous. This process consumes 12-20 kWh of energy per ton of pulp.

The function of the rotor is three-fold: the rotor 1) agitates and mixes the suspension, 2) produces mechanical stresses sufficient to the break down bales and fiber bundles, and 3) clears the screen at the bottom of the tank shown in Fig. 7a. Because rotor is responsible for pumping, processing and screening, it must be carefully designed. At the project start up, the goal was to reduce the process energy consumption by 30 %. The design was constrained by the requirement that the quality of the produced pulp must remain the same.

New rotor was designed based on CFD analysis. Pulper flow fields were simulated using ANSYS CFX 14.5 software using water as a fluid. SST-k-omega turbulence model was used with the curvature and rotation correction terms. A steady state solution was calculated for a periodic computational domain consisting of one blade and its surroundings. The vat and rotor domains were connected with a frozen rotor interface with an appropriate pitch change.

Whereas the calculation of the energy consumption is straightforward with CFD, the calculation of the pulp quality is not. We thought of different criteria that could represent the quality. Fiber treatment is clearly proportional to the stresses and strains induced to them during the process. Also the high level of turbulence can indicate fiber bundle breakdown. Sufficient fiber treatment was guaranteed by requiring that the total shear force of the rotor blades was higher than in the original design.

The original and new rotors were tested at Valmet Fiber Technology Center (FTC) in Inkeroinen, Finland. Figure 8 shows the calculated and measured power versus rotational speed for the original rotor. The affinity law for pump power predicts that rotor power increases as the cube of rotational speed. This behavior was expected and also observed with the original rotor, see Fig. 8. Because of such a predictable behavior, we designed the new rotor by performing simulations only at 300 rpm. There is an unexplained 30 % difference between the measured and simulated power. We proceeded by ignoring the difference and assuming that the even though the absolute values are not correct, the changes in the design are predicted correctly. In other words, we assume that both the actual and simulated power consumption change in the same direction upon a change in the rotor geometry.

The results of preliminary test runs with the new rotor were promising. Even though power consumption of the redesigned rotor was practically the same as that of the original rotor, the intensity of the mechanical treatment was increased considerably and pulping could be carried with 50 % less time. Thus, with the same product quality, the energy consumption of the process could be reduced by 50 %. Fiber treatment was enhanced because flow velocities were generally higher in the new design which caused stronger impacts. The new rotor shape is also such that the area of impacts is larger. We estimate that further savings of 10 % might be possible by reducing the rotor's rotational speed. Research is being done to determine the rheological properties of water-fiber suspensions to be able to provide more accurate CFD predictions.

Fig. 7. Original rotor.

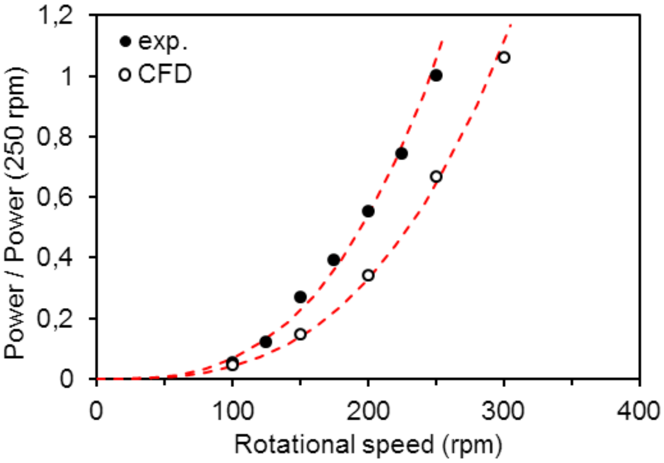

Fig. 8. Pulper power measured at Valmet FTC in Inkeroinen (exp.) and calculated with CFD (CFD). Dashed lines show cubic fitted curves.

Summary

The Finnish paper industry consumes a vast amount of energy in pumping fluids and in processing of fiber suspensions. EFEU project has focused on realizing energy efficiency improvement both in equipment and systems level. Pumping system consume up to 50 % of industrial energy consumption in industrial countries. With the use of optimal electrical motors, the energy consumption of pumping systems could be reduced approximately 2-4 %. Variable speed control can be applied for example in reservoir pumping application with approximately 30-40 % energy savings. We have demonstrated how the time constraint can be taken into account while energy consumption is minimized, which extends the applicability of energy minimizing speed control. The energy consumption of pulping process is 12-20 kWh/ton of pulp. New energy efficient pulper designed in this project consumes 50 % less energy than the old one. We estimate that further 10 % savings are possible using variable speed control also in this application.

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