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Tero Ahonen, Santeri Pöyhönen, Maija Leino, Pekka Pasanen

VIEWS ON THE FUTURE FLUID HANDLING SYSTEMS, RESULTS OF FINNISH EFFICIENT ENERGY USE RESEARCH PROGRAM

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This work has been in the Efficient Energy Use (EFEU) research program coordinated by CLIC Innovation Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes.

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Abstract

Abstract

Authors	Tero Ahonen, Santeri Pöyhönen, Maija Leino, Pekka Pasanen
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Efficient Energy Use (*EFEU*) research program was founded in 2011 to assess industry-level problems in energy efficiency in Finland and is now being finalized. EFEU's research focus has all the time been in improving fluid handling systems with systems-level approach through advanced control methods and also by developing next-generation equipment, such as pumps, agitators and pulpers for the paper industry. A distinctive characteristic of the EFEU program is the close co-operation between universities and equipment manufacturers to realize new systems-level results instead of just focusing on individual devices.

This report summarizes existing commercial and state-of-the-art designs for fluid handling systems, main outcomes of the EFEU research program related to fluid handling systems and eventually conducted interviews on future fluid handling systems concerning their technical characteristics and role in the digitalized, service-related world.

Tiivistelmä

Kirjoittajat	Tero Ahonen, Santeri Pöyhönen, Maija Leino, Pekka Pasanen
Nimi	Views on the future fluid handling systems, results of Finnish Efficient Energy Use research program
Vuosi	2016
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Tutkimusohjelma *Energian tehokas käyttö* eli *EFEU* (*Efficient Energy Use*) käynnistettiin vuonna 2011 tavoitteena löytää järjestelmätason ratkaisuja esimerkiksi teollisuuden virtausjärjestelmien toimintaan liittyen ja on päättynyt vuoden 2016 lopussa. Tutkimusohjelman tavoitteena on ollut parantaa virtausjärjestelmien energiatehokuutta järjestelmälähtöisellä ajattelutavalla kehittämällä muun muassa uusia ohjaustapoja sekä laitteistoja paperiteollisuuden sovelluksia varten. Yksi EFEU-tutkimusohjelman ominaispiirteistä on ollut yliopistojen sekä yritysten läheinen yhteistyö järjestelmätason ratkaisujen kehittämiseksi yksittäisten laitteiden sijaan.

Tämä raportti tarjoaa yhteenvedon nykyisistä virtausjärjestelmistä, EFEU-tutkimusohjelman päätuloksista virtausjärjestelmiin liittyen ja lopuksi haastattelujen avulla kerättyjä näkemyksiä tulevaisuuden virtausjärjestelmistä ja niiden roolista digitaalisessa, palveluliiketoimintaan perustuvassa yhteiskunnassa.

Preface

Energy efficiency is a key element in mitigating climate change. International Energy Agency has estimated that almost 40% of the global CO_2 emission reductions required to limit global warming less than 2 °C by 2050, can be achieved by improving end-use energy efficiency. A major factor in the global energy consumption are electric-motor driven fluid handling systems. Improving of their material and energy efficiency through new design selection, control and diagnostic methods opens new export possibilities to system manufacturers and service providers.

This report provides views of future fluid handling systems based on the outcomes of the Efficient Energy Use (EFEU) research program. Firstly the report provides description of present state-of-the art in certain fluid handling systems. Then, EFEU outcomes are introduced in detail, providing grounds to future views gathered by interviews with EFEU industrial partners. As future energy systems will have more service-based actions, this development can also consider fluid handling systems that can be remotely monitored and controlled.

This work was carried out in the Efficient Energy Use (EFEU) research program coordinated by CLIC Innovation Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes. EFEU program developed system level energy efficient solutions and services for fluid handling systems and regional energy systems. EFEU consortium consisted of 11 industrial partners and 5 research organizations. The industrial partners were ABB Oy, Empower IM Oy, Fortum Oyj, Fortum Power and Heat Oy, Gasum Oy, Helen Oy, Sulzer Pumps Finland Oy, SKF Oy, Valmet Technologies Oy, Wärtsilä Finland Oy and Wellquip Oy. The research partners were Aalto University, Lappeenranta University of Technology, Tampere University of Technology, VTT Technical Research Centre of Finland and Åbo Akademi University. The five-year program was started in 2012 and finished in 2016. The budget of the program was 12 million euros.

Juha Leppävuori
EFEU Program Manager

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1 Introduction to fluid handling systems considered in EFEU program

Fluid handling systems account for the major part of industrial electricity consumption in electric motors. As an example, a single paper mill is operated with hundreds of electric motors driving pumps, fans, mixers, pulpers and different kinds of conveyors with each one having power consumption ranging from tens to hundreds of kilowatts (see Fig. 1). Operating costs are the most important source of costs in fluid handling systems. Because of the high energy demand of fluid handling systems, small improvements in efficiency can still lead to significant reduction in their life-cycle costs (Almeida et al. 2003). Especially energy intensive equipment is found in forest industry, for example in refining and pulping processes and in the pumping of fluids.

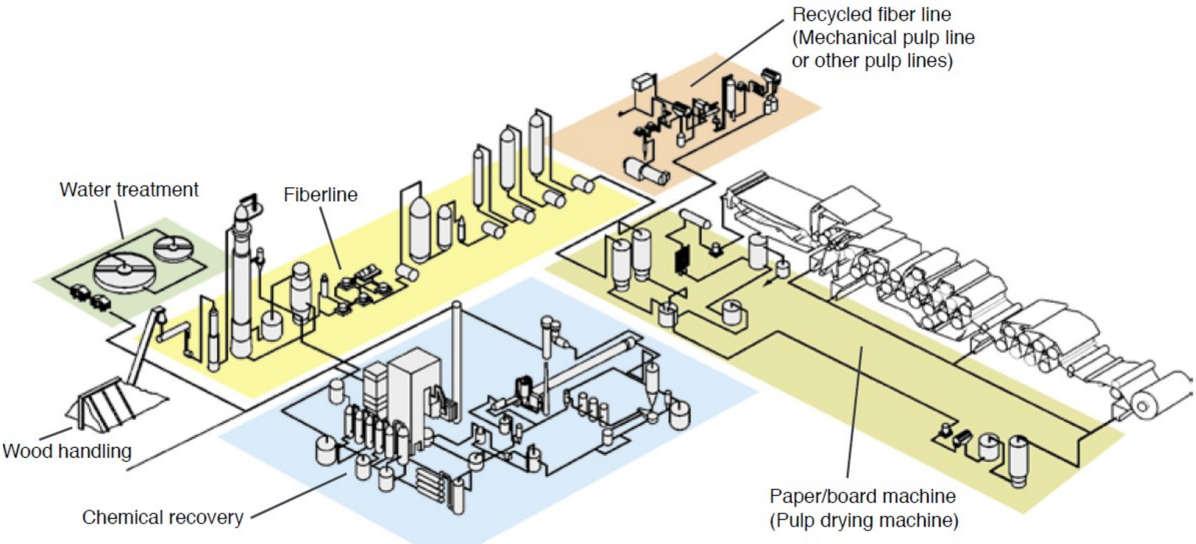

Fig. 1. End-use applications for electric motors in a paper mill.

As the improvement in individual component efficiency (in % of kW_{out}/kW_{in}) does not always directly lead to improved system energy efficiency (in kWh/m^3), a systems-level approach should be used in the development, selection and control of fluid handling systems. This is one of the main ideas behind the Efficient Energy Use (EFEU) program founded in 2011, which provides solutions for industry-level problems in energy efficiency in Finland. Since its beginning, the EFEU research program 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. 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 a distinctive characteristic of the EFEU program.

The purpose of this report is to introduce existing commercial and state-of-the-art designs for fluid handling systems, main outcomes of the EFEU research program related to these systems and to eventually provide views on future fluid handling systems concerning their technical characteristics, physical appearance and role in the digitalized, service-related world.

2 Present state of the art - what is limiting their improvement?

This section introduces present commercial and state-of-the-art designs for fluid handling systems. The main focus is on the pumping systems that are driven with an electric motor at variable speeds. This section is based on the EPE'14 conference paper "*Comparison of electric motor types for realising an energy efficient pumping system*", the EEMODS'15 conference paper "*Progress in energy efficiency in fluid handling systems*" and the INTROEQUIPCON 2016 conference paper "*Design of low specific speed pumps using CFD, 3D-printer and air as a fluid*" written by EFEU research teams from Universities of Technology in Lappeenranta and in Tampere.

2.1 Pumping systems

Pumps are a primary end-use application for electric motors in the industrial sector. Therefore, efficiency regulations set for electric motors also contribute to the energy efficiency of pumping systems. Similar to the international efficiency (IE) classification for low-voltage three-phase motors, industrial pumps are required to fulfil the minimum efficiency index (MEI) classification, which limits the least efficient pumps out of the European market during forthcoming years (European Commission 2012). As Europump (European Association of Pump Manufacturers) is currently forming an energy efficiency index (EEI) for the whole pumping system considering also its operation, there is a need for studying how a next generation, more energy efficient pumping system should be realised and designed instead of the present fashion to have a separately designed pump, motor and frequency converter in the same setup.

A good forerunner for realising such a pumping system can be found from circulator pumps that must be variable-speed-driven, are regulated with the energy efficiency index (Europump), and nowadays have an integrated construction allowed by their small dimensions. Fig. 2 illustrates an example of a modern circulator pump that fulfils the existing EEI requirements and is equipped with a variable-speed-driven permanent magnet synchronous motor. According to manufacturer claims, hydraulic and mechanic losses of the circulator pump are minimised with optimised hydraulic design (including a three dimensional impeller) and the use of carbon bearings. The pump has also control electronics equipped with algorithms for driving the pumping system with optimized energy efficiency.

Fig. 2. Exploded view of Grundfos MAGNA3 circulator pump comprising also the motor and control electronics in the same casing (Grundfos 2012).

Typical industrial pumping systems represent an opposite design approach, as they comprise a radial-flow centrifugal pump coupled to an induction motor that is possibly driven with a separate frequency converter, allowing variable-speed operation of the pump. The effect of possible misaligning on the system reliability is often compensated with the use of flexible coupling between the pump and motor. The pump and motor are typically located on the same baseplate as illustrated in Fig. 3.

Compared with circulator and wastewater pumps, it can be clearly seen how industrial pumping systems are composed of individual devices that originate from different manufacturers. Although this allows easy replacement of broken devices in the pumping system, this approach cannot realise the most compact or energy efficient pumping system, since devices are not optimised to work with each other. As examples, both the pump and motor have their own bearing construction, available motors are not optimised to be solely used with pumps, and the frequency converter has to be manually configured for the driven pump-motor combination by the end-user.

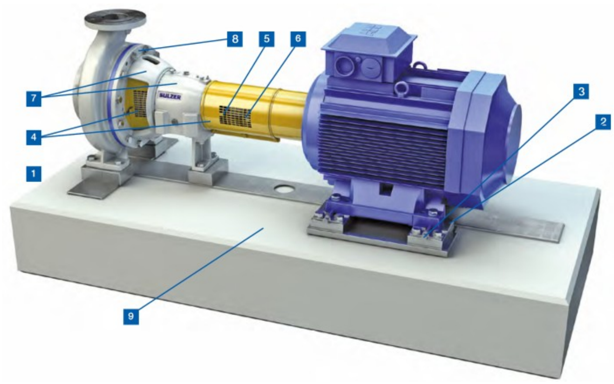

Fig. 3. Exemplary installation of typical industrial pumping system shown in present-day marketing material (Sulzer 2013).

In addition to the use of separate devices, present pumping systems are dictated by the principal dimensions given in the ISO 2858 standard for end-suction pumps. While pump manufacturers are improving their products, a radial-flow pump still has to have similar dimensions and look similar as in 1970's. This also occurs in electric motors, which normally have dimensions according to IEC frame size standard 60072-1 with the sixth edition published in 1991. A practical example of similar dimensions over the decades is shown in Fig. 4, where a Serlachius pumping system from 1970s and a Sulzer pumping system from 2006 are shown side by side: although there is a visible development both in the pump and motor construction, the Sulzer pumping system still has the same kind of setup and similar kind of dimensions as the Serlachius system from 1970s.

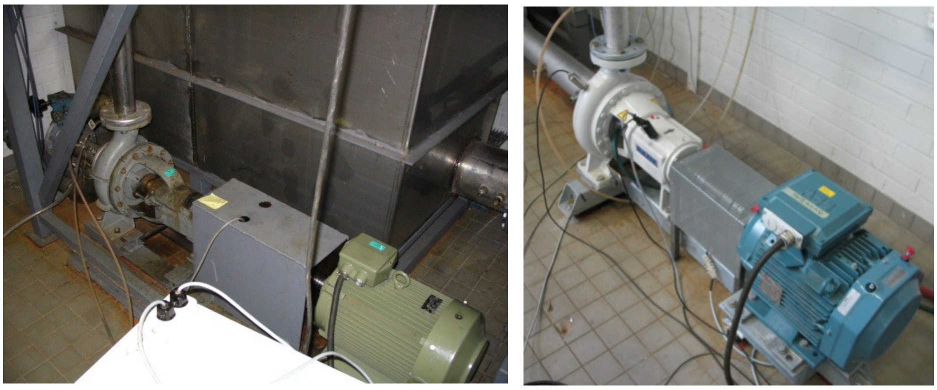

Fig. 4. Two laboratory pumping systems in the previous pump laboratory of Lappeenranta University of Technology. Serlachius pumping system on the left was acquired in 1970's and the Sulzer pumping system on the right in 2006.

When these pumping systems are compared to modern circulator pumps, it is evident that there is still efficiency improvement potential in pumping systems with a new structure for the pump that is not limited by existing standards. This is supported by the fact that manufacturers have been able to improve the pump efficiency with optimised impeller and volute design, although the principal dimensions of the pump have remained unchanged. With an integrated pump and motor design, it may be even possible to improve system efficiency and reliability and simultaneously lower manufacturing costs due to a smaller amount of components in the device.

2.2 Pulpers

Pulpers are used to mix dry fibers with water to produce a homogeneous water-fiber suspension. Fiber bales are dropped into a water filled tank, which is agitated by the rotor located at the bottom of the tank (see Fig. 5). The process can run either in batch-wise or continuous mode. In batch operation, bales of 250 kg are fed to the machine, and the process is run until the water-fiber consistency requirement is satisfied.

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. Because the rotor is responsible for pumping, processing and screening, it must be carefully designed. The main difficulty in rotor design is the unknown turbulence behaviour of the water-fiber suspension, for which there are no well-defined models. Therefore, energy savings potential of 30-50 % can be well available in the present-day pulpers, if an improved rotor geometry can be developed.

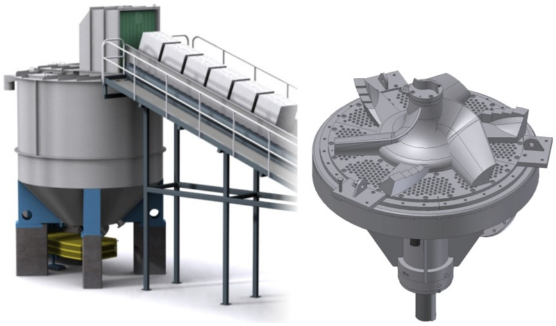

Fig. 5. Example of present-day Valmet VMi pulper unit.

2.3 Electric motors

The induction motor (IM) can be considered 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. The 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 device has been a 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, IE2 and IE3. For a four-pole (1500 rpm), 15 kW motor these classes mean minimum efficiencies of 88.7, 90.6 and 92.1 percent, respectively (see Fig. 6).

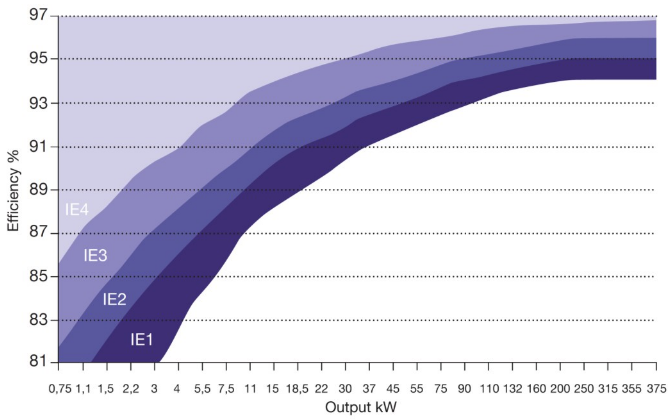

Fig. 6. International efficiency classes given for four-pole electric motors according to IEC standards IEC/EN 60034-30:2008 and IEC/TS 60034-31.

Since the induction motor is not the most efficient nor compact motor technology available nowadays, it leaves room for 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 induction motors, 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 (see Fig. 7). As a practical example, the first commercial PMSMs with IE5 level were introduced in 2014. For the 15 kW four-pole motor, this would mean the minimum efficiency of over 94.3%.

Another higher-efficiency alternative for the IM is the synchronous reluctance motor (SynRM), which can be considered a combination of the IM and the PMSM technologies. The advantage of the basic SynRM is that it is cheap to manufacture, as it only needs iron and copper. They are also available in the IE4 efficiency level, meaning 93.9% motor efficiency with a VSD supply according to (ABB 2013).

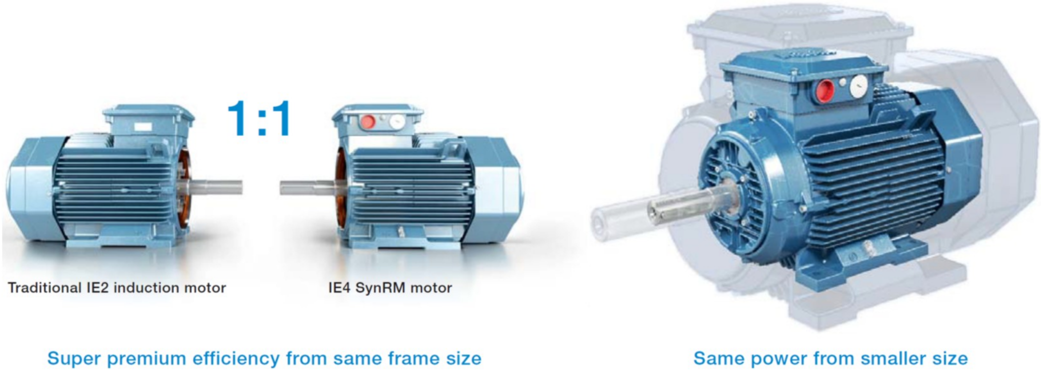

Fig. 7. Benefits available by upgrading an induction motor with a synchronous reluctance motor.

2.4 Variable-speed drives

Variable-speed operation of pumps and fans is one of the key factors to energy efficiently operating systems, as it allows the regulation of output flow or pressure without adding hydraulic losses into the surrounding process. Typically, variable-speed operation is realized by using a frequency converter to operate the electric motor at desired rotational speeds: the common setup is to have a voltage source inverter that operates the electric motor by varying its supply voltage and frequency.

Modern frequency converters are versatile devices, providing several application-specific monitoring and control functions for the motor-driven device. As an example, internal PID controllers and control functions for multi-pump systems are standard features in pump-focused frequency converters. Another increasing trend in frequency converters is to have an integrated programmable logic controller (PLC) that allows modification of the converter, and hence system operation according to specific needs.

Some frequency converters also allow sensorless estimation of the pump or fan operating state, which can be further used for identification and monitoring purposes. This is primarily possible by accurate estimates for the motor rotational speed (n_{est}) and shaft torque (T_{est}), which are commonly available in vector and direct-torque-controlled frequency converters. When these estimates are supplied to the characteristic-curve-based model for the pump or fan operation, for instance the flow rate and specific energy consumption can be determined without additional sensors.

In certain applications, variable-speed operation can be used to optimize both the pumping system and surrounding process operation in terms of energy efficiency. Fig. 8 provides an example of a central heating system equipped with thermostats that act as control valves. In these systems, the circulator pump must be able to provide enough pressure to the radiators regardless of the thermostat valve setting. The required pressure for radiators is ensured by operating the circulator pumping system with a constant pressure reference; traditionally this has been realized with the use of a pressure relief valve and currently with the use of variable-speed operation.

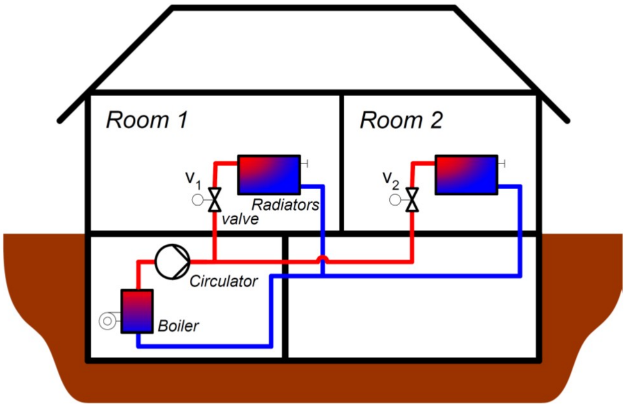

Fig. 8. An example of central heating system having a circulator pump and two radiators equipped with thermostat valves.

However, the use of constant pressure reference is not the most energy efficient approach for these systems, where the primary task is to provide flow to the radiators according to the present need, not a constant pressure into the system. From a control point of view, this means that as thermostat valves close down because of the reduced need for flow[1], rotational speed of the circulator pump can be decreased to result in the opening of thermostats and the reduced flow rate with less power consumption. This feature is nowadays available in several frequency converters under the name advanced pressure control or flow compensation.

Another notable example of energy saving control scheme is applied in some variable-speed drives for wastewater systems. The control scheme monitors the energy consumption of reservoir drainage events and selects either a lower or higher constant rotational speed for the next run based on the energy consumption of two previous drainage events, as the amount of transferred fluid is assumed to remain constant. This control scheme is easy to realize without additional measurements, as it relies on the internal power estimation of the VSD and can automatically find the best constant rotational speed for the pumping system operation in wastewater stations.

[1] Closing the thermostat valve increases friction loss factor k. This has a detrimental effect on the system energy efficiency and specific energy consumption E_s.

3 EFEU outcomes and results

EFEU research program has developed and studied methods and tools that allow the use of the systems-level approach when designing, selecting and testing new fluid handling systems. This section summarizes deliverables providing more information about these outcomes

3.1 Novel design and selection methods

Improved designing of fluid handling devices requires accurate models for the fluid behavior, which has been under study in Tampere University of Technology. In his Master's thesis titled as "*Measurement of flow properties of pulp suspension*", Kari Mustalahti studied the behaviour of bleached birch fibers when they are forming pulp suspension together with water. For this study, a special measurement setup was designed and built. The obtained measurement results were applied to determine the most suitable material model (now being Herschel-Bulkley model) to use for modelling the flow behaviour of birch pulp. When the material models were evaluated with a computational fluid dynamics program, consistent results were obtained for the test setup. It was also noted that more accurate models for the flow velocity behaviour would improve the quality of material model, which is why this topic is under study by Eetu Ojala in his Master's thesis project named as "*Development of flow model for water-fiber suspensions*".

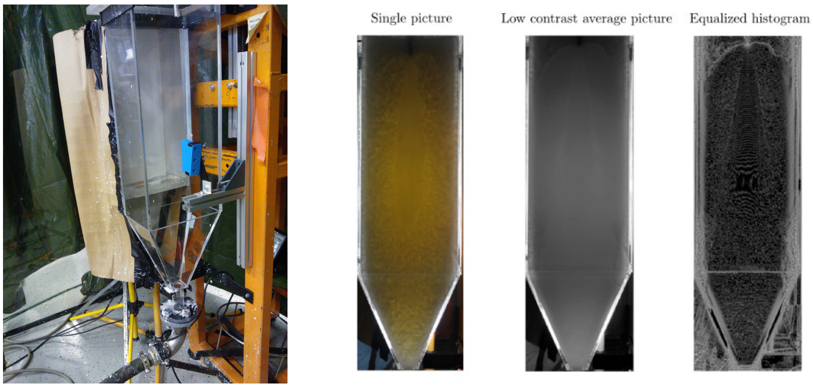

Fig. 9. Eetu Ojala's test setup at TUT with example on test measurement results.

An area where improved flow models can be utilized is the design of centrifugal pumps. Traditionally new pump impeller and volute designs are a result of iterative development process, where the most promising designs must be manufactured and tested in practice. Since the manufacturing of single pump impeller may cost around 2000 euros and is quite time consuming, more cost-effective testing options can give multiple benefits in the product development phase.

Such a solution is the use of 3D printed plastic impellers in a test setup, where pump performance is measured by applying the air as pumped medium. This approach is under study and development by Pekka Pasanen at Tampere University of Technology. In 2013, he studied the effects of using air as the pumped medium in his Master's thesis "*Performance of centrifugal pump as a fan*". As main results, he noted that the pump characteristic curves can be defined with the air-based measurement setup, and it provides results whether there has been efficiency improvement due to impeller geometry modifications. These results have helped Pekka in the development of test measurement setup that he is currently using in the testing of new impeller geometries.

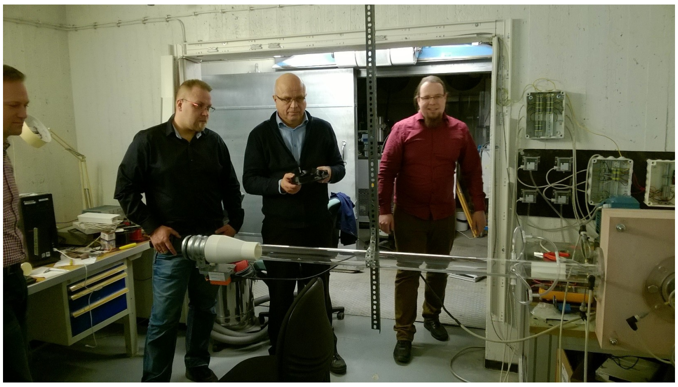

Fig. 10. The air-based measurement setup at TUT designed by Pekka Pasanen.

In 2016, first measurement results for new impeller designs were published in "*Design of low specific speed pumps using CFD, 3D-printer and air as a fluid*" conference paper. There modified version of open pump impeller shown in Fig. 11 was evaluated both with CFD calculations and with air-based measurement setup, when it was used in the original and modified pump volute. First test results are encouraging as the pump performance (in terms of output flow and head) has increased with the modified impeller, indicating of efficiency improvement in the range of several percentage units.

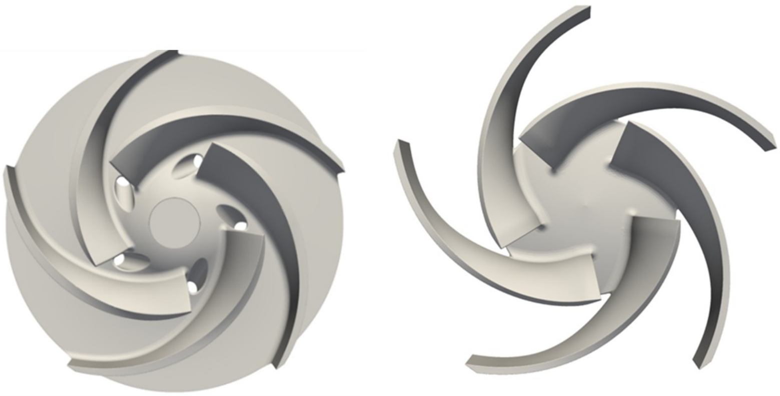

Fig. 11. Figures of the tested pump impellers, original on the left and modified version on the right.

For systems-level selection of fluid handling devices, researchers in Lappeenranta University of Technology have provided two selection tools named as Pumping System Optimization Tool (PSOT) and Savings Calculator for Centrifugal Pumps (SCCP).

Unlike traditional component selection tools, which concentrate only in one component of a pumping system at a time, the Pumping System Optimization Tool selects the best combination of pump, motor and frequency converter for the given process. With this kind of approach, the entire selection of the pumping system setup can be done by only one software and the total energy conversion efficiency of the process can be optimized. PSOT also calculates the lifecycle costs for the optimized system and shows how it is distributed in investment, operating and maintenance costs. The tool was presented in the EPE 2013 conference paper "*Component selection tool to maximize overall energy conversion efficiency in a pumping system*" by Tamminen et al. The Matlab-based implementation of PSOT was on display in the EFEU final seminar in Helsinki on October 31st 2016. Its main window is shown in Fig. 12.

Fig. 12. The main window of the Pumping System Optimization Tool.

The Savings Calculator for Centrifugal Pumps is a software tool for quick analysis of the viability of change of flow control method from throttling to variable-speed operation. Even though variable-speed operation in a pumping system is already quite an old invention, throttle control is still used very widely, even if the energy efficiency of a pumping system could be often remarkably improved by using variable-speed control. Therefore, the main purpose of SCCP is to reliably show that in most cases significant energy and financial savings could be achieved, by the relatively small investment in a variable-speed drive. SCCP is not the only one of its kind - many similar tools already exist, for example ABB PumpSave and Vacon Save. Compared to them, SCCP requires less input information and has a different calculation approach in modelling of pumping system devices. In addition, SCCP also provides an option to input the flow profile of the process with time stamped flow and save detailed PDF report.

The PSOT and SCCP tools were evaluated and compared by Lauri Nygren in his EEMODS'15 conference paper "*Automatic determination of pumping system energy efficiency with EFEU software tools*". It was found that they can both give indicative results about the profitability of replacing throttle control with variable-speed control, which enables making informed decisions to improve the energy efficiency of pumping systems.

3.2 Soft-sensor-based monitoring and control methods

This section summarizes the WP2 deliverables, which have covered topics related to soft-sensor-based monitoring and control methods for fluid handling systems. More specifically, the published conference and journal papers have studied the use of a frequency converter to enable sensorless methods, with which the operation of a fluid handling system can be monitored. The presented methods aim to provide means to 1) estimate the operation state of a system, to 2) identify the characteristics of the system and for 3) the energy efficient control of fluid handling systems.

An introduction to soft-sensor-based methods was given by Ahonen et al. in the EEMODS'13 paper "*Sensorless frequency-converter-based methods for realizing life-cycle cost efficient pumping and fan systems*". The study discusses the available methods and the benefits they can bring. The potential of a VSD in optimizing the life-cycle costs of pumping and fan systems is presented in Fig. 13.

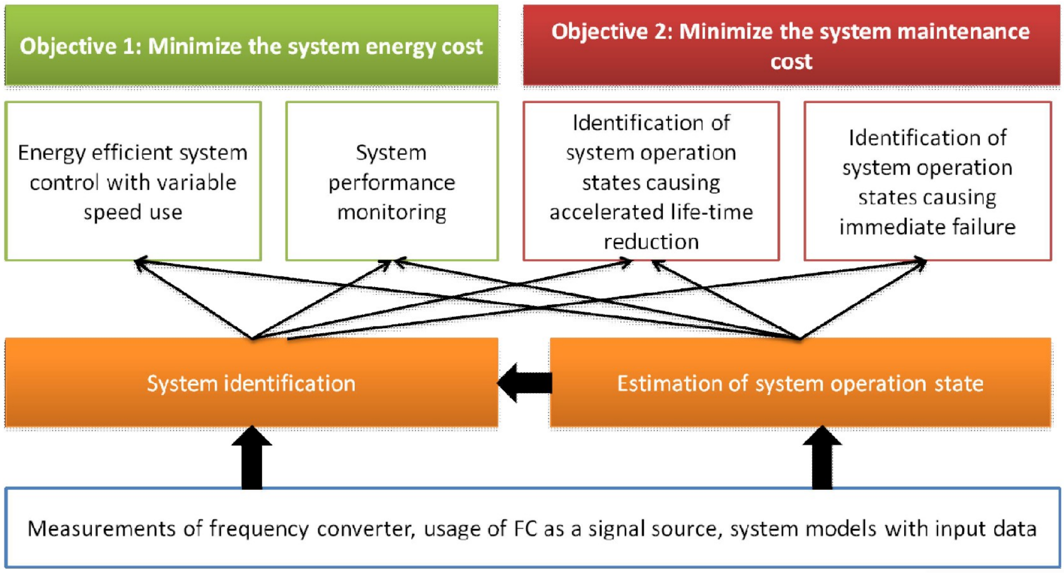

Fig. 13. Functions of a frequency converter in LCC efficient pumping and fan systems.

In their article "*Comparison of model-based flow rate estimation methods in frequency-converter-driven pumps and fans*" published in the journal Energy Efficiency in November 2013, Tamminen et al. assessed the performance of multiple methods, which can be employed in a frequency converter to estimate the flow rate produced by a pump or a fan. As a novelty, the paper also proposed a new method and compared its accuracy with that of the already existing methods. According to the laboratory measurements, the proposed estimation method is the most accurate and reliable of the assessed model-based estimation methods (see Fig. 14).

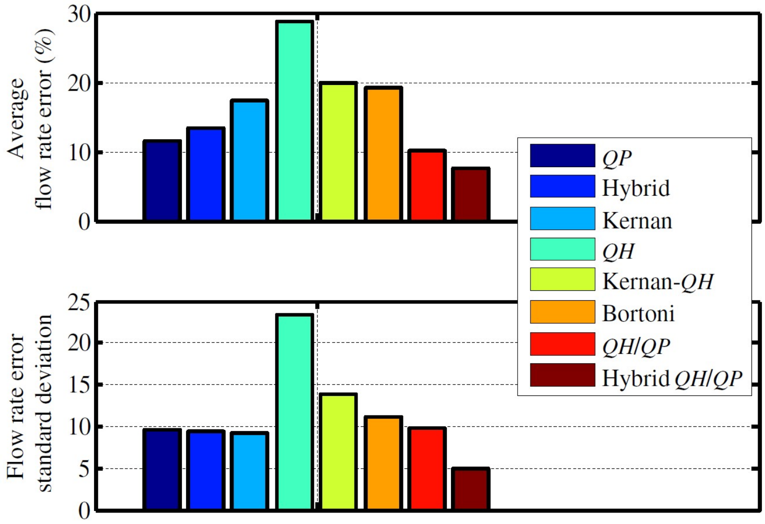

Fig. 14. Average error and standard deviation in estimates provided by the evaluated estimation methods. The *QH*/*QP* and hybrid *QH*/*QP* methods are the ones suggested in the article.

The conference paper "*Sensorless estimation of the pumping process characteristics by a frequency converter*", which was published in September 2013 in the 15th European Conference on Power Electronics and Applications by Ahonen et al. studied the possibility to use a frequency converter to identify the characteristics of the process surrounding a pump. As a result, two methods were proposed. It was concluded that identification of the process surrounding the pump can reveal a minimum rotational speed at which flow is produced, which can help to avoid running the pump at zero flow rate. In addition, the process static head estimate provided by system identification can be used in the determination of the most energy efficient (based on the specific energy consumption E_S) rotational speeds for the system. System identification can also provide reference values for the system specific energy consumption, which can be utilized in determining the best energy efficiency areas of pumps. The principles of the presented methods are visualized in Fig. 15.

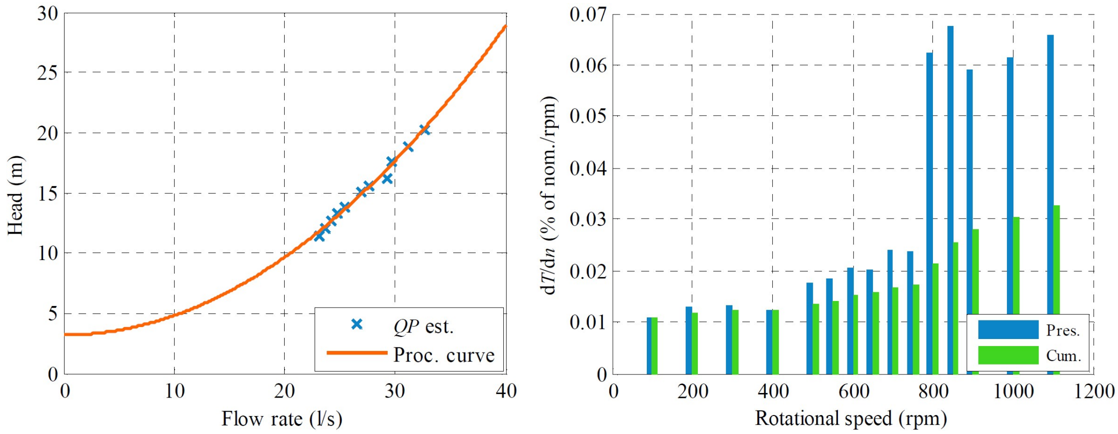

Fig. 15. A operation state estimation method is used to define the process curve, meanwhile torque estimates are monitored to detect the rotational speed at which flow is produced.

Information about the pump operational state and surrounding process parameters provide grounds for optimized control of the pumping system. Further research resulted in methods to optimize the control of a pump from the point of view of the whole system's energy efficiency.

In the article "*Energy-efficient control strategy for variable speed-driven parallel pumping systems*" published in the journal Energy Efficiency in December 2012, Viholainen et al. introduced a new control strategy, with which parallel variable speed-driven pumps can be operated. The proposed control strategy was tested with laboratory measurements, which indicated that a parallel pumping system will operate more energy-efficiently with the new control strategy than with traditional rotational speed control. Using the proposed control strategy should also lead to a lower risk of mechanical failure of the controlled pumps due to the strategy being able to run the pumps in their recommendable operating regions. Results of the paper are visualized in Fig. 16.

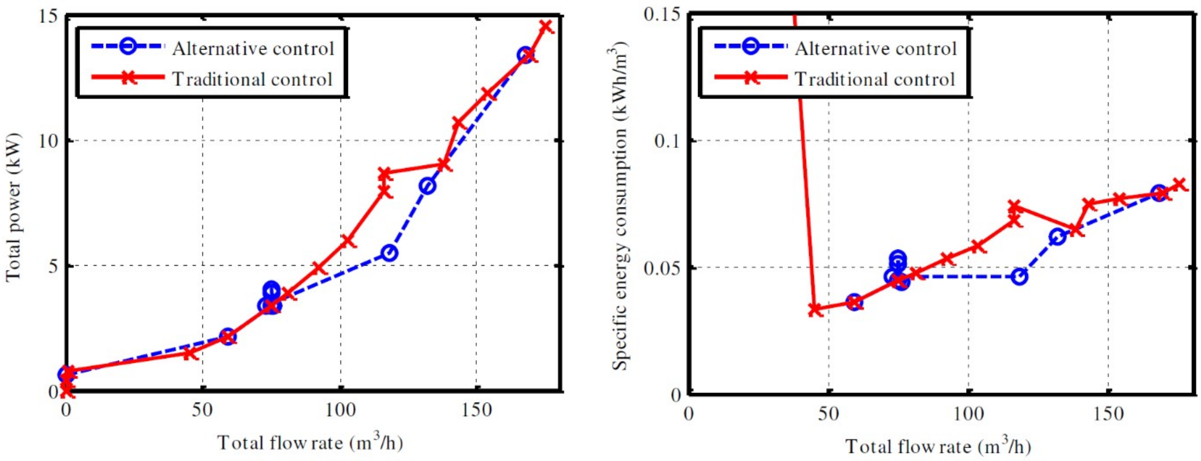

Fig. 16. Estimated total input power and specific energy consumption of parallel-connected pump drives in the alternative control and the traditional speed control.

In their paper "*Sensorless specific energy optimization of a variable-speed-driven pumping system*" published at the EEMODS'13 conference, Tamminen et al. introduce a way to minimize the specific energy consumption of a pumping system. The method relies on the ability of a frequency converter to monitor a pump's operating state without sensors and its algorithm is able to find the rotational speed that will yield the minimum specific energy consumption. The method can be used in applications without strict time limits for the pumping process, including, for instance, reservoir-filling tasks. The specific energy-optimizing algorithm presented in the paper is shown in Fig. 17.

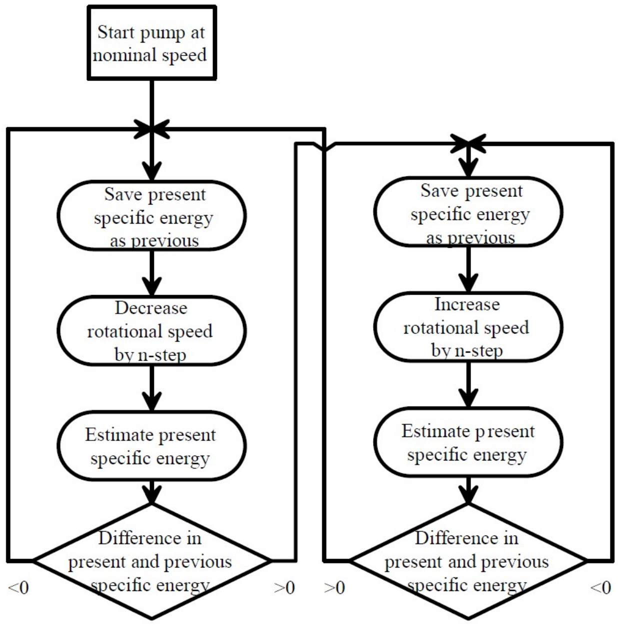

Fig. 17. A simplified presentation of the algorithm, which can be used to minimize the specific energy consumption of a pumping system.

In their article "*Energy efficiency optimizing speed control method for reservoir pumping applications*" published in the journal Energy Efficiency in July 2014, Ahonen et al. propose a method, which can find the energy-efficiency-wise optimum rotational speed in a reservoir pumping application with a changing process static head. The method was studied with simulations and laboratory measurements and was found to be able to significantly improve the energy efficiency of a fixed-speed operated reservoir pumping system.

3.3 Soft-sensor methods for remote diagnostics of industrial fluid handling systems

Besides the sole method development for VSDs, their use in different industrial applications has been studied during the EFEU research program. An example of such is the remote monitoring of fan operation and condition.

Initially, in the paper "*Detection of mass increase in a fan impeller with a frequency converter*" published in the IEEE Transactions on Industrial Electronics in September 2013, Tamminen et al. studied the possibility to use a frequency converter to detect the build-up of contaminants on a fan impeller. The method relies on the ability of a frequency converter to produce an accurate torque step to the motor shaft and estimate the resulting motor rotational speed. Laboratory measurements showed that contamination build-up can be detected and its amount quantified with the presented method. The topic was studied further in the conference paper of Tamminen et al., "*Variable Speed Drive-Based Fan Impeller Contamination Build-Up Detection: Industrial Case Study*", which was presented in the 17th Conference on Power Electronics and Applications in September 2015. The previously presented method was modified and applied to an industrial fan system with results showing that a frequency converter can be used in detecting the build-up of contaminants, which could lead to impeller imbalance and further to a failure of the fan system. In Fig. 18, development of the impeller inertia estimate during the case monitoring period is shown.

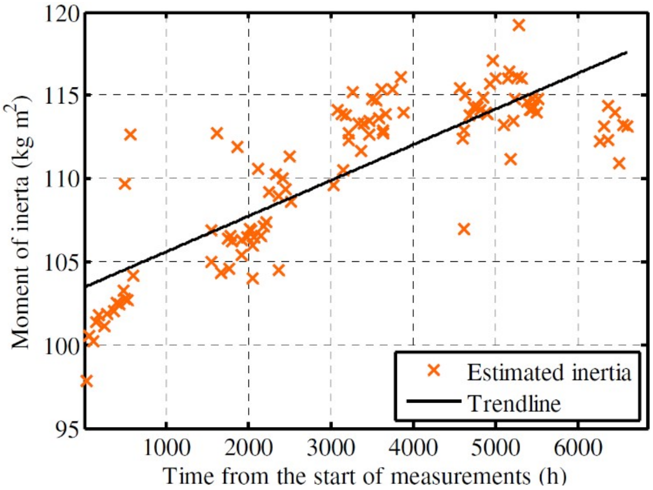

Fig. 18. Estimated fan impeller inertia. The trendline is based on the inertia estimates of the first 5500 hours of the monitoring period. A partial clean-up of the impeller was conducted after approximately 5500 hours of operation, which can be seen as a decrease in the estimated moment of inertia.

The monitoring of industrial compressors was also studied. Järvisalo et al. published the article "*Soft-sensor-based flow rate and specific energy estimation of industrial variable-speed-driven twin rotary screw compressor*" in the IEEE Transactions of Industrial Electronics in May 2016. In the paper, methods for estimating the compressor flow rate, the specific energy consumption and compressed-air system volume identification were proposed. The flow rate estimation method was found to be accurate, and it could be used as a redundant flow sensor. It was also concluded that the specific energy consumption map and changes in it over a course of time could be a feasible way of condition monitoring of a VSD twin rotary screw compressor. Fig. 19 shows a specific energy consumption map generated with the presented method.

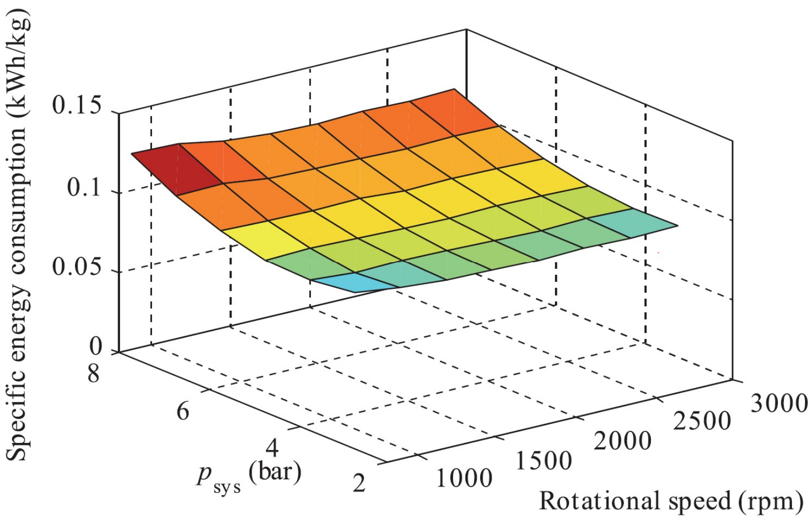

Fig. 19. The specific energy consumption map for a twin rotary screw compressor.

In the industry, centrifugal pumps exist in large numbers and thus auditing their energy-efficiency on a large scale can be laborious and expensive. Because of this, audits may often take into account only the pumps most vital to a certain process, leaving many old or poorly sized pumps operating inefficiently. In the paper by Pöyhönen et al., "*Specific-speed-based pump flow rate estimator for large-scale and long-term energy efficiency auditing*", which is currently under consideration for publication in the Springer Energy Efficiency journal (submitted in April 2016 and as of October 31st 2016 under review), a fast-to-employ flow rate estimator for centrifugal pumps is presented. The estimator employs a measurement or estimate of a pump's shaft power and the pump's nominal values and can cost-efficiently highlight inefficiently running pumps out of large pump populations. Fig. 20 illustrates the principle of the presented method.

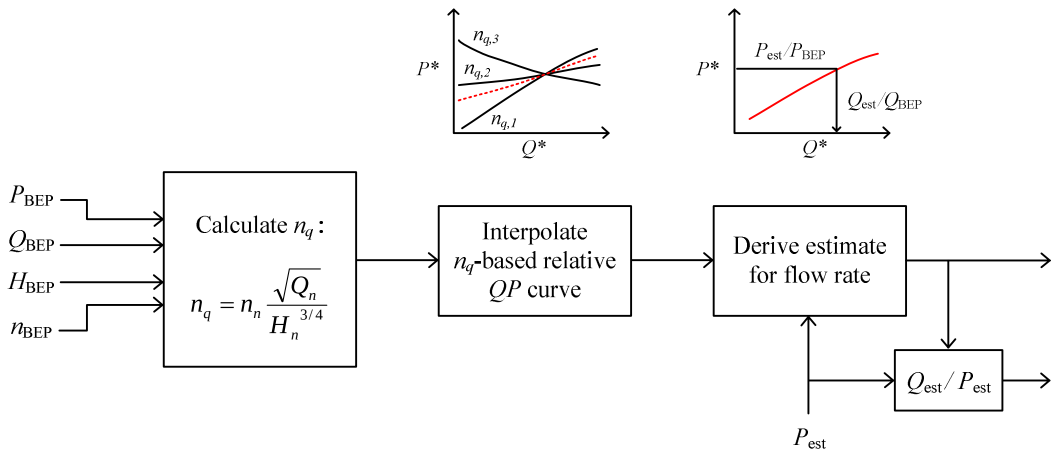

Fig. 20. The principle of the specific-speed-based flow rate estimator.

3.4 New device designs

In fluid handling systems, devices are typically designed as separate units that can be coupled to each other. This approach cannot realise the most compact or energy efficient pumping system, since devices are not fully optimised to work with each other. For example, both the pump and motor have their own bearing construction, available motors are not optimised to be solely used with pumps, and the frequency converter has to be manually configured for the driven pump-motor combination by the end-user. On top of it all, typical pumping systems are installed onto a concrete baseplate, which considerably increases total weight and material costs of the fluid handling system installation (see Fig. 3).

Based on the research findings concerning the pump and motor efficiencies, there is still efficiency improvement potential in pumping systems, which can be realised with a new structure for the pump that is not limited by existing standards. This is supported by the fact that manufacturers have been able to improve the pump efficiency with optimised impeller and volute design, although principal dimensions of the pump have remained unchanged. With the integrated pump and motor design, it may be even possible to improve system efficiency and reliability all the while reducing manufacturing costs due to a smaller amount of components in the device.

To this end, the EFEU project has studied two new device designs for pumping and pulper applications. Fig. 21 introduces the integrated pump-motor concept device that comprises a small-sized SynRM connected with a common shaft and custom adapter to the Sulzer radial-flow centrifugal pump. Compared to the traditional setup shown in Fig. 3, this concept device is easier to install, has less bearings, and there is a smaller risk of installation errors that are a usual cause of additional system maintenance and failure costs.

The concept device is a concrete result of co-operation between universities and industry, where new ideas have been tested in order to make more compact pumping device that can be more efficient and still as cost-effective as the typical industrial pumping system. Based on the conducted measurements published in Eetu Hyyppä's Bachelor thesis "*Life cycle inventory for electric motor devices*", this concept device has roughly the same efficiency as the pump and motor would have as separate devices, which can be improved with new pump impeller and volute designs, and also with the use of ferrite magnets in the motor, meaning ferrite magnet assisted SynRM as the motor technology.

Fig. 21. EFEU concept device comprising a small-sized synchronous reluctance motor integrated with Sulzer radial-flow centrifugal pump.

EFEU research program has also realized new pulper designs that have been able to notably reduce the energy consumption of the pulping process due to shortened task execution time. Improved designs have become possible through the improved models for the water-fiber fluid behaviour. When the new pulper rotor design was tested in Inkeroinen test mill, it was found to be able to decrease the pulper power consumption and especially halve the mixing time, leading to ~30-50% energy savings available with rotor replacement.

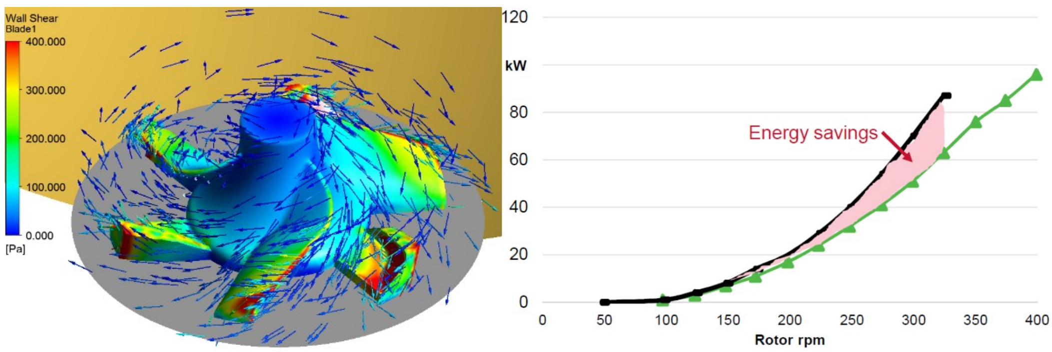

Fig. 22. New pulper rotor design was first tested with CFD calculations and then measured in Inkeroinen test mill.

Both of these devices have sprung new ideas that will be further tested by partners in their own projects. For instance, energy efficiency of horizontal pulpers has been modelled and studied by Atte Rättyä his Master's thesis "*CFD analysis of a horizontal pulper*" that provides background information to Valmet.

4 Future of fluid handling systems

Fluid handling systems will stay an essential part of society also in the future. EFEU outcomes introduced above give an idea on technical development expected to happen in future generation of variable-speed fluid handling systems. As the future development will also be affected by digitalization and providing of services related to the fluid handling systems, interviews with industry partners from ABB and Sulzer were conducted to gather their opinions considering the future of fluid handling systems. by EFEU research teams from Universities of Technology in Lappeenranta and in Tampere.

4.1 Motors and pumps as a service

In the first conducted interview with Jouni Ikäheimo from ABB motors, the current role of original equipment manufacturers (OEMs) was seen a potential place for future development: a "leasing model", where manufacturers lease their equipment to customers, could be developed in the future. The service could be extended to apply to the operation of the leased device, with the lessor taking care of operating the leased equipment.

Today, system owners who acquire and own fluid handling systems don't necessarily possess the expertise to operate new equipment in the most efficient way or have the knowledge to maintain it. Thus, the role of manufacturers and suppliers is developing into a direction where they may assume greater responsibility in equipment operation and maintenance. The development of fluid-handling services is supported also by the perception that customers are often willing to pay for a product or service in instalments, even if it means the overall life-cycle cost would ultimately be higher than a corresponding one-time investment. However, in some cases the needs and objectives of a fluid handling system owner may require them to have full control over their processes themselves, which doesn't necessarily rule out a leasing model, but may make accepting an equipment operating service impossible.

Customization poses a challenge to the fluid-handling system leasing model. Leased products may have to be modified to suit the needs of customers. Such customization may render the products unusable to other customers.

4.2 Remote monitoring and control - new service business?

In addition to simply providing flow for processes, fluid handling services of the future can make use of the Internet connectivity of devices. The possibility of providing efficient process control and optimized maintenance as a service was discussed in the interview with ABB's Jukka Tolvanen, Juha Saukko and Olli Alkkiomäki. The following concerns and ideas were raised in the discussion.

Firstly, the possibility and need to change the VSD parameters through remote control based on the detected change in operating conditions was brought front. This can provide new business possibilities to companies like ABB. This also brought the question of data ownership, is it owned by the drive manufacturer (service provider) or the system end-user? This question also concerns the location of data, should it be stored locally to the drives or to the Internet-based cloud service? Also following points were brought front in this discussion:

Most feasible models for the service business are closely linked to the questions above. Then one should determine that who should own the equipment that are provided as a service: should it be the equipment manufacturer, the end-user or an investment company that provides leasing as a part of it financing services? Another interesting question is the pricing principle that should reflect life-cycle costs of the fluid handling system – could the performance-related €/m^3 unit be used as the main pricing principle, or should there be capacity-related (m^3/h) pricing options as with the Internet subscriptions?

As the hardware price of power electronics is decreasing and hence decreasing the available marginal profit in the sales of variable-speed drives, it leads to question if the drive control firmware and control&diagnostic methods introduced in this report could be provided as leased service or as separately charged apps that are also feasible in other manufacturer's systems. Then the drive manufacturer such as ABB could benefit on its software development and also provide variable-speed drives with higher marginal costs thanks to the income from apps.

Concluding point from ABB interview was the focus to the whole life-cycle of fluid handling systems. The fact with electric motors is that even though we have IE4 and soon IE5 equipment available, most of the used equipment are IE2, because the end-user and system integrator focus is still in the investment costs. What if service business could provide a way to make the leap from IE2 to IE4 and IE5 relatively fast?

4.3 Reliable pumps for the customer

The interview with Saku Vanhala and Sami Virtanen from Sulzer gave practical views on their customer needs and the current markets for industrial pumps. Close-coupled or integrated pumps are available in Sulzer's product portfolio, but so far only few have been sold to special applications, where installation area is critical factor. Easy maintainability and reliability have also been mentioned as critical factors to end customers, which has preferred the design of pumps as separate devices with their own bearings. This underlines the pre-commercial nature of research carried out in EFEU research program, where integrated concept devices have been developed for pumping applications. However, Sulzer recognises the improvement in motor technologies and efficiency values, as IE4 class SynRM's are provided to the customers as an alternative to the induction motor.

5 Summary and final words

Fluid handling systems account for the major part of industrial electricity consumption in electric motors. As the improvement in individual component efficiency (in % of kW_{out}/kW_{in}) does not always directly lead to improved system energy efficiency (in kWh/m^3), a systems-level approach should be used in the development, selection and control of fluid handling systems. This is one of the main ideas behind the Efficient Energy Use (EFEU) research program founded in 2011, which has provided several solutions and also a model of co-operation that has the systems approach in its genes.

As some examples of EFEU program outcomes, new device designs and service-related monitoring solutions have been developed and published during the project duration. As fluid handling systems will stay an essential part of society also in the future, program outcomes summarized in this report are certainly coming to future products and services in the forthcoming years.

References

ABB. Low voltage IE4 synchronous reluctance motor and drive package for pump and fan applications, ABB Motors and Generators, 2013.

Ahonen T, Tamminen J, Ahola J, Niinimäki L, Tolvanen J. *Sensorless estimation of the pumping process characteristics by a frequency converter*. 15th European Conference on Power Electronics and Applications (EPE 2013).

Ahonen T, Viholainen V, Tamminen J, Tolvanen J. *Sensorless frequency-converter-based methods for realizing life-cycle cost efficient pumping and fan systems*. 8th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'13).

Ahonen T, Tamminen J, Montonen J. *Comparison of electric motor types for realising an energy efficient pumping system*. 16th European Conference on Power Electronics and Applications (EPE'14-ECCE Europe).

Ahonen T, Tamminen J, Viholainen J, Koponen J. *Energy efficiency optimizing speed control method for reservoir pumping applications*. Energy Efficiency (2015) 8:117–128.

de Almeida A., Fonseca P., Falkner H. and Bertoldi P.: *Market transformation of energy-efficient motor technologies in the EU*, Energy Policy, Vol. 31, pp. 563–575, 2003.

European Commission: *Regulation no. 547/2012 implementing directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for water pumps*.

Europump: *Energy Efficiency of Circulators*, pdf document, accessed on 14th December 2013, available at http://europump.net/uploads/20111208_EuP_Lot_11_circulators_-_general_explanations_EEI_-_modified_versionV3_1__for_website.pdf

Grundfos: *MAGNA3 – More than a pump*, Grundfos, Bjerringbro, 2012.

Hyyppä E. *Life cycle inventory for electric motor devices*. Bachelor's thesis, Lappeenranta University of Technology, 2016.

Järvisalo M, Ahonen T, Ahola J, Kosonen A, Niemelä M. *Soft-sensor-based flow rate and specific energy estimation of industrial variable-speed-driven twin rotary screw compressor*. IEEE Transactions on Industrial Electronics, Vol. 63, No. 5, May 2016.

Karvinen R, Pasanen P. *Design of low specific speed pumps using CFD, 3D-printer and air as a fluid*. 3rd International Rotating Equipment Conference, 2016.

Lindstedt M, Ahonen T, Tolvanen J. *Progress in energy efficiency in fluid handling systems*. 9th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'15).

Mustalahti K. *Vesikuitususpension virtausominaisuuksien mittaus*. Master's thesis, Tampere University of Technology, 2015.

Nygren L, Ahonen T, Tamminen J, Tolvanen J. *Automatic determination of pumping system energy efficiency with EFEU software tools*. 9th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'15).

Ojala E. *Development of flow model for water-fiber suspensions*. Master's thesis, Tampere University of Technology, 2017.

Pasanen P. *Performance of centrifugal pump as a fan*. Master's thesis, Tampere University of Technology, 2013.

Pöyhönen S, Ahonen T, Ahola J, Punnonen P, Hammo S. *Specific-speed-based pump flow rate estimator for large-scale and long-term energy efficiency auditing*. To be published in Springer Energy Efficiency Journal.

Rättyä A. *CFD analysis of a horizontal pulper*. Master's thesis, Tampere University of Technology, 2016.

Tamminen J, Kosonen A, Ahonen T, Ahola J, Immonen P, Muetze A. *Component selection tool to maximize overall energy conversion efficiency in a pumping system*. 15th European Conference on Power Electronics and Applications (EPE 2013).

Tamminen J, Viholainen J, Ahonen T, Tolvanen J. *Sensorless specific energy optimization of a variable-speed-driven pumping system*. 8th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'13).

Tamminen J, Viholainen J, Ahonen T, Ahola J, Hammo S, Vakkilainen E. *Comparison of model-based flow rate estimation methods in frequency-converter-driven pumps and fans*. Energy Efficiency (2014) 7:493–505.

Tamminen J, Ahonen T, Ahola J, Niemelä M, Tahvanainen A, Potinkara A. *Detection of mass increase in a fan impeller with a frequency converter*. IEEE Transactions on Industrial Electronics, Vol. 60, No. 9, September 2013.

Tamminen J, Ahonen T, Ahola J, Pöyhönen S, Tiainen T. *Variable Speed Drive-Based Fan Impeller Contamination Build-Up Detection: Industrial Case Study*. 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe).

Viholainen J, Tamminen J, Ahonen T, Ahola J, Vakkilainen E, Soukka R. *Energy-efficient control strategy for variable speed-driven parallel pumping systems*. Energy Efficiency (2013) 6:495–509.

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