LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Department of Electrical Engineering
MASTER'S THESIS

ENERGY EFFICIENCY PARAMETERS IN VARIABLE SPEED DRIVES

The department head of the Department of Electrical Engineering has approved the topic of this Master's thesis.

Examiners: Professor Pertti Silventoinen
D.Sc. Markku Niemelä

Supervisor: M.Sc. Jukka Tolvanen

Lappeenranta 6 May 2009

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ABSTRACT

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Energy efficiency parameters in variable speed drives

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49 pages, 16 figures, 6 tables and 6 appendixes

Examiners: Professor Pertti Silventoinen
D.Sc. Markku Niemelä

Keywords: Variable speed drive, energy-efficiency, parameters, pump, flow control

The main purpose of this thesis is to measure and evaluate how accurately the current energy saving calculation in ABB's new variable speed drive ACS850 works. The main topic of this thesis is energy-efficiency parameters.

At the beginning of this thesis centrifugal pump, squirrel cage motor and variable speed drive, including some equations related to them, are being introduced. Also methods of throttling control and variable speed drive control of centrifugal pumps are being introduced. These subjects are introduced because the energy saving calculation in ACS850 is related to the centrifugal pumps usually driven by squirrel cage motors. The theory also includes short section about specific energy of pumping.

Before measurements the current energy saving calculation of ACS850 is being introduced and analyzed. The measurements part includes introduction of measuring equipment, measurement results, summary and analysis of the measurements.

At the end of this thesis a proposal for an improvement to the current energy saving calculation is being introduced and few proposals are made for new energy-efficiency parameters, which could be added to variable speed drives. At the end are also thoughts about new possible areas for energy saving calculations to be implemented.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Sähkötekniikan osasto

Jani Kasurinen

Taajuusmuuttajan energiatehokkuusparametrit

Diplomityö

2009

49 sivua, 16 kuvaa, 6 taulukkoa ja 6 liitettä

Tarkastajat: Professori Pertti Silventoinen
TkT Markku Niemelä

Hakusanat: Taajuusmuuttaja, energiatehokkuus, parametrit, pumppu, virtaussäätö

Tämän työn päätavoite on mitata ja arvioida miten tarkasti nykyinen energiansäästölaskenta ABB:n uudessa taajuusmuuttajassa ACS850 toimii. Työn pääaiheena ovat energiatehokkuusparametrit.

Työn alussa esitellään keskipakopumppu, oikosulkumoottori ja taajuusmuuttaja sekä muutamia niihin liittyviä yhtälöitä. Myös keskipakopumpun kuristussäätö ja pyörimisnopeussäätö esitellään. Nämä aiheet esitellään, koska energiansäästölaskenta ACS850:ssä liittyy keskipakopumppuihin, joita tyypillisesti ajetaan oikosulkumoottoreilla. Teoria sisältää myös lyhyen osion pumppauksen ominaisenergiasta.

Ennen mittauksia esitellään ja analysoidaan ACS850:n nykyinen energiansäästölaskenta. Mittausosio sisältää mittalaitteiston esittelyn, mittaustulokset, mittausten yhteenvedon ja analysoinnin.

Työn lopussa esitellään parannusehdotus nykyiseen energiansäästölaskentaan ja tehdään muutamia ehdotuksia uusista energiatehokkuusparametreista lisättäväksi taajuusmuuttajiin. Lopussa on myös ajatuksia uusista mahdollista alueista energiansäästölaskennalle.

PREFACE

Now at the end of April 2009 my master's thesis is nearly complete. The process of writing it and doing the measurements for it has been very interesting and educating. I got pretty familiarized with pumping systems, their control methods and energy-efficiency related to them.

The thesis has been made by the ABB's request. My supervisor at ABB was M.Sc. Jukka Tolvanen. To him and Lic.Sc. Simo Hammo at the Lappeenranta University of Technology I want to give my greatest thanks for this opportunity of making my thesis. Also Jukka I want to thank for his time and dedication and for all the help he provided during the process. Many thanks also belong to my examiners at the Lappeenranta University of Technology, Professor Pertti Silventoinen and D.Sc. Markku Niemelä, for their advice and guidance. Also huge thanks belong to M.Sc. Juha Viholainen and M.Sc. Tero Ahonen at the Lappeenranta University of Technology for their indispensable assistance during the measurements and for their valuable advices.

Many thanks to Erkki Nikku and other staff at the Lappeenranta University of Technology, who put together the measuring equipment and helped during the measurements. I also want to thank those people at ABB, who provided me information and advice during my thesis project. Thanks also belongs to all those who taught me during my academic studies.

Last, but not least, I want to thank all my fellow students who helped me thru my studies and student life. Great thanks belong also to my foster parents and family who gave their support during my studies.

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Jani Kasurinen

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Appendix B: Measured axis powers, average axis power and its linear fitting
Appendix C: Throttling controlled pumping results
Appendix D: VSD controlled pumping results
Appendix E: Results for saved power calculations
Appendix F: Results of newly calculated saved powers.

SYMBOLS AND ABBREVIATIONS

Greek letters

η	Efficiency	[%]
ρ	Density	[kg/m^3]
φ	Phase angle	[°]

Roman letters

A	Area	[m^2]
C	Correction factor	
D	Pipe diameter	[m]
E	Energy	[kWh]
f	Frequency	[1/s]
g	Gravitational factor	[m/s^2]
I	Current	[A]
n	Rotational speed	[1/min]
P	Power	[W], [kW]
p	Pressure, Pole pairs	[Pa], -
Q	Flow rate	[m^3/s]
s	Slip	
T	Torque	[Nm]
U	Voltage	[V]
v	Flow velocity	[m/s]

Subscripts

0	Initial value
1	New value, Inlet
2	Outlet
d	Variable speed drive
d,in	Drive input
d,out	Drive output
dyn	Dynamic head
geo	Geodetic head

harm	Harmonic losses
hyd	Hydraulic
in	Input
in(nom)	Nominal input
loss	Losses
m	Motor
m,in	Motor input
m,out	Motor output
max	Maximum
motorloss	Motor losses
nom	Nominal
nomloss	Nominal loss
p	Pump, venturi tube
r	Friction, rotational
s	Synchronous, Specific
sinloss	Sine losses
st	Static
tot	Total
venturi	Venturi tube

Acronyms

VSD	Variable speed drive
IEA	International Energy Agency

1. INTRODUCTION

Because of continuously increasing price of energy, emission limitations and greenhouse effect energy saving has become even more important and interesting topic. Consumers also want to know how much energy they are consuming and how much it could be saved. According to many investigations pumping systems have a large energy saving potential by optimizing the system and adjusting the drive. The ratio between needed investments and saved energy and the actual savings are things, which surely interest the consumers. Some variable speed drive, VSD, manufacturers have developed means of measuring and displaying directly on the VSD's display the amount of energy and its value, which the drive can save compared to other controlling methods. This saved energy is also presented as reduction in CO_2 emissions in metric tons.

The main objective of this study is to measure how accurately one of the ABB's new variable speed drive, ACS850, calculates the saved energy compared to the throttling control in pumping systems. For this, measurements are made and the results are compared to the value displayed by the variable speed drive. At the beginning of this thesis centrifugal pump, squirrel cage motor and variable speed drive are introduced briefly and also the methods of throttling control and VSD -control. Also the basic power calculations for pumps, motors and VSDs are being introduced.

After presenting the measurement results, improvements for the current energy saving calculation are proposed and some new possible energy-efficiency parameters are introduced. Also few schemes for new areas, where energy saving could be presented to end users, are briefly discussed.

2. CENTRIFUGAL PUMPS

Only centrifugal pumps are being introduced, because the VSD used on the measurements calculates energy saving compared to the throttling control of centrifugal pumps.

2.1 Characteristic curves

Most common curves describing the pump and the system attached to it are pump’s head curve, pump’s power curve, pump’s efficiency curve and system curve. Pump’s head curve illustrates the net work done on a unit of water by the pump impeller as a function of flow. Different rotating speeds and impeller sizes have their own head curves. Pump’s power curve illustrates the needed power for certain flow. Efficiency curve illustrates how well the power fed into the pump is transformed into hydraulic power.

Losses generated by the piping can be determined by examining the piping’s characteristic curve aka system curve. Losses are formed of the static head, H_{st}, which is constant and independent of the flow and the head caused by the piping, H_{dyn}, which is dependent of the flow. (Volk 2005, 56-70)

By drawing the pump curve and the system curve into same coordinates can be determined the pump’s operating point. In figure 1 the pump’s operating point is determined.

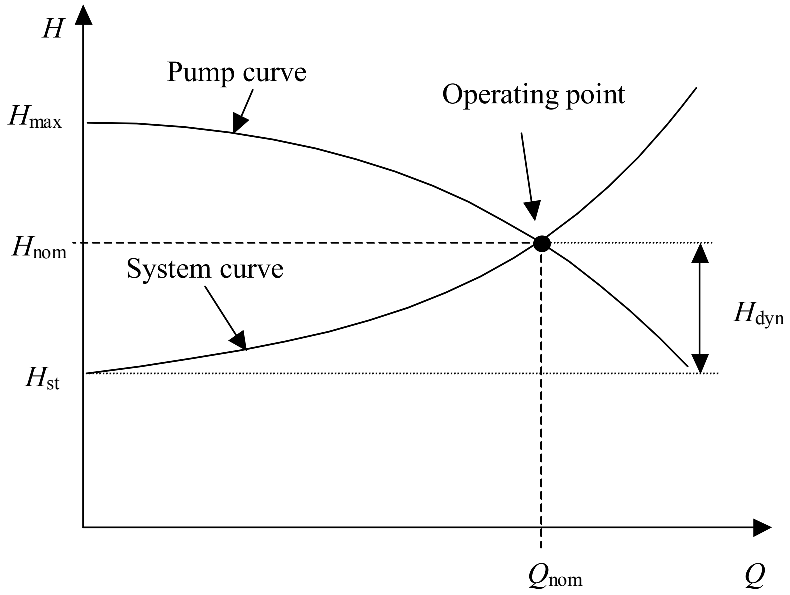

Figure 1. Determination of the pump's operating point.

2.2 Power and efficiency of a centrifugal pump

Power transferred into the liquid by the pump, hydraulic power, can be calculated with equation

$$P_{\text{hyd}} = Q \cdot \rho \cdot g \cdot H \,, \tag{1}$$

where

P_{hyd} Hydraulic power [kW]

Q Volume flow [m^3/s]

ρ Density of the pumped liquid [kg/m^3]

g Acceleration of gravity [m/s^2]

H Total head [m]

If pipe diameter and flow velocity are known the volume flow can be calculated with equation

$$Q = vA \,, \tag{2}$$

where

v Flow velocity [m/s]

A Pipe's cross-sectional area [m^2]

The required power on the pump's axis can be calculated with equation

$$P_\mathrm{p} = \frac{Q \cdot \rho \cdot g \cdot H}{\eta_\mathrm{P}}, \tag{3}$$

where

P_p Required power on the pump's axis [kW]

η_p Efficiency of the pump

Pump's efficiency tells how much of the shaft power is transformed into hydraulic power in the pump and it can be expressed with equation

$$\eta_\mathrm{p} = \frac{P_\mathrm{hyd}}{P_\mathrm{p}} \tag{4}$$

Motor's efficiency can be expressed with equation

$$\eta_\mathrm{m} = \frac{P_\mathrm{m,out}}{P_\mathrm{m,in}}, \tag{5}$$

where

η_m Motor's efficiency

$P_\mathrm{m,out}$ Shaft power [kW]

$P_\mathrm{m,in}$ Motor's input power [kW]

Assuming that $P_\mathrm{p} = P_\mathrm{m,out}$ total efficiency of the pumping is therefore

$$\eta_\mathrm{tot} = \eta_\mathrm{p} \cdot \eta_\mathrm{m} \tag{6}$$

Motors shaft power can also be calculated with equation

$$P_\mathrm{m,out} = \frac{2\pi n \cdot T}{60}, \tag{7}$$

where

n Motor's rotational speed [1/min]

T Torque provided by the motor [Nm]

If a venturi tube is used to measure the velocity of the flow, then the volume flow can be calculated with equation

$$Q = C_p A_0 \sqrt{\frac{2\Delta p_{\text{venturi}}}{\rho\left[\left(\frac{D_0}{D_1}\right)^4 - 1\right]}} = C_p A_1 \sqrt{\frac{2\Delta p_{\text{venturi}}}{\rho\left[1 - \left(\frac{D_1}{D_0}\right)^4\right]}}, \quad (8)$$

where

$\Delta p_{\text{venturi}}$	p_1-p_0, pressure difference in the venturi tube [Pa]
A_0	Pipe's cross-sectional area at upstream [m^2]
A_1	Pipe's cross-sectional area at downstream [m^2]
D_0	Pipe's upstream diameter [m]
D_1	Pipe's downstream diameter [m]
C_p	Correction factor depending on the used venturi tube and flow rate

Figure 2 illustrates the basic structure of a venturi tube.

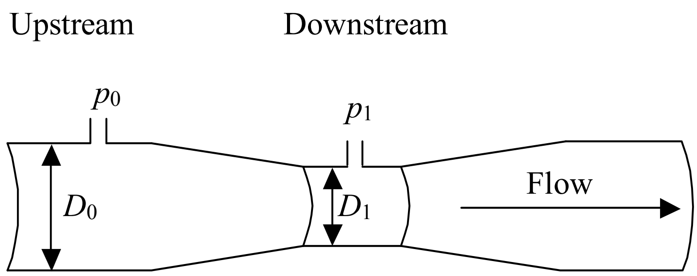

Figure 2. Basic structure of a venturi tube.

(Wirzenius 1978, Taskinen 2008, 39-40)

2.3 Head of a centrifugal pump

Pump's head is formed of geodetic head, friction head, pressure head and velocity head. At operating point pump's total head is the same as required by the system.

Geodetic head is the elevation difference between water levels at suction vessel and delivery vessel. The flow resistance in piping system forms the friction head. Pressure head must be taken into account, if either of the tanks is pressurized. If both of the tanks are in the same pressure, for example both are open, then the pressure head is zero. Velocity head means the needed energy to accelerate the liquid to a certain speed. In high head systems velocity head is insignificant, but in low head systems it should be taken into considerations. (Aranto 2008, 17-18)

Total head can be calculated with equation

$$H = H_{\mathrm{geo}} + \frac{p_2 - p_1}{\rho \cdot \mathrm{g}} + \frac{v_2^2 - v_1^2}{2\mathrm{g}} + \sum H_{\mathrm{r}} \, , \qquad (9)$$

where

H_{geo}	System's geodetic head [m]
p_2-p_1	Pressure difference between vessels [Pa]
v_1	Flow velocity at suction inlet [m/s]
v_2	Flow velocity at discharge outlet [m/s]
ΣH_{r}	Friction head [m]

Total head can be divided into static and dynamic part called static head and dynamic head. Static head consists of geodetic head and pressure head. Dynamic head consists of velocity head and friction head.

Static head can be then written as equation

$$H_{\mathrm{st}} = H_{\mathrm{geo}} + \frac{p_2 - p_1}{\rho \cdot \mathrm{g}} \qquad (10)$$

And dynamic head as equation

$$H_{\mathrm{dyn}} = \frac{v_2^2 - v_1^2}{2\mathrm{g}} + \sum H_{\mathrm{r}} \qquad (11)$$

Total head can be then written again as equation

$$H = H_{\mathrm{st}} + H_{\mathrm{dyn}} \qquad (12)$$

(Wirzenius 1978, 57-59)

2.4 Affinity laws

When centrifugal pump's rotational speed changes the new values for flow rate, head and power can be calculated using affinity laws. The affinity laws are valid only when the efficiency remains constant.

When varying rotational speed, affinity laws are:

$$Q = Q_0 \cdot \frac{n}{n_0}, \tag{13}$$

where

Q_0 Initial flow rate [m^3/s]

n_0 Initial rotating speed [1/min]

$$H = H_0 \cdot \left(\frac{n}{n_0}\right)^2, \tag{14}$$

where

H_0 Initial head [m]

$$P = P_0 \cdot \left(\frac{n}{n_0}\right)^3, \tag{15}$$

where

P_0 Initial power [kW]

(Wirzenius 1978, 74-76)

2.5 Throttling control

In throttling control the pump runs at nominal speed and valve in the discharge pipe adjusts the flow rate to wanted value. Figure 3 illustrates the principle of throttling control.

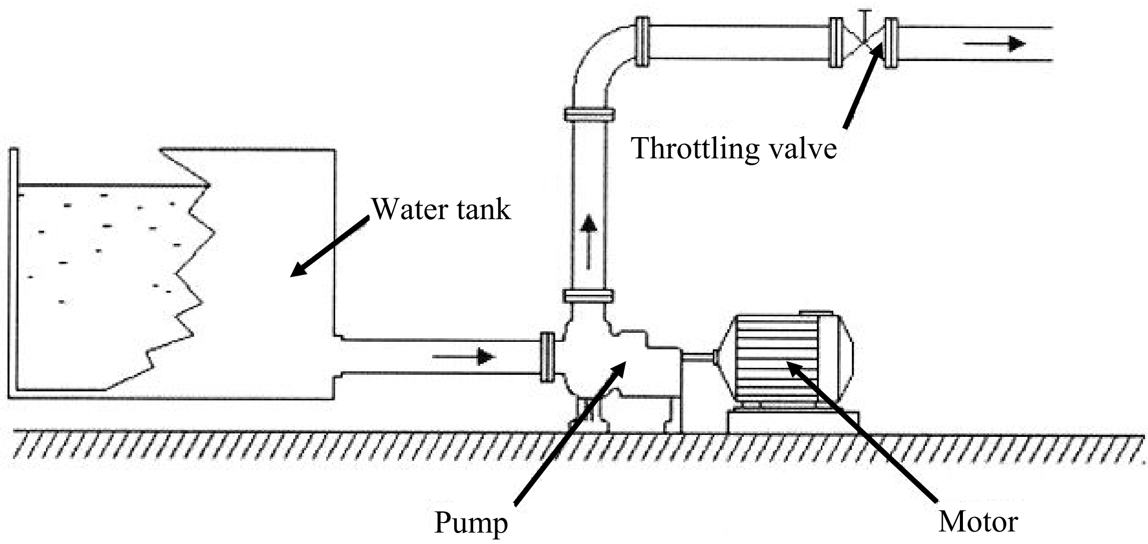

Figure 3. This figure illustrates the principle of throttling control, where the flow is controlled with a throttling valve. The motor and the pump are running at static speed while the valve is either turned to be more open or more closed to achieve the desired flow rate. (Viholainen 2007, 29)

Throttling control is widely used because its installation is cheap and easy. Reducing the flow by turning the valve increases the head generated by the pump. Increase in head is wasted energy. Figure 4 shows how the system curve shifts when the flow is reduced by the throttling control. (Karttunen 2004, 253 ; Ryti 1980, 26)

Total efficiency of throttling control is pump's efficiency multiplied by motor's efficiency as equation 6 expresses.

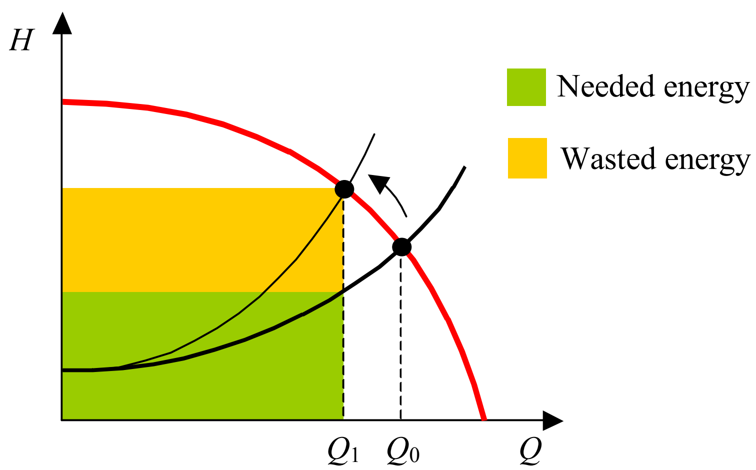

Figure 4. Affects of throttling control to system curve and head.

2.6 Variable speed drive control

VSD control has become more popular choice of flow control because of its many benefits. It is energy saving, fairly easy to install on existing systems, control range is wide without massive energy losses, optimization is possible, lowers the load on bearings and on pumps and smooth start and stop is possible. (Viholainen 2007, 33)

Figure 5 shows a VSD controlled pumping system where a VSD is used to control the motor's rotating speed and to collect data from the pressure transmitters, which can then be used as control parameters.

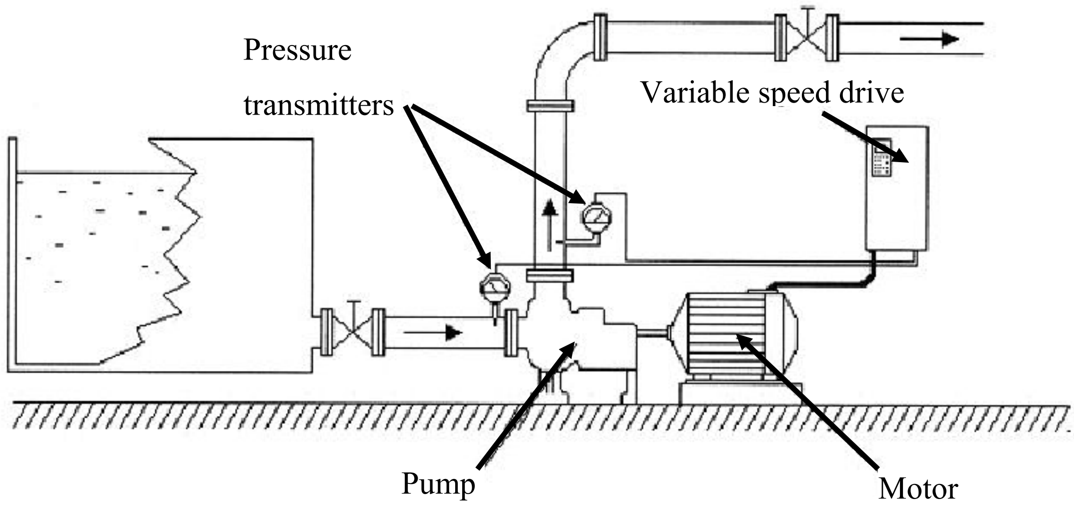

Figure 5. This figure illustrates VSD controlled pumping system, where a VSD is used to control the speed of the motor and thus the pump's rotational speed. Pressure transmitters can be used for feedback control or just for monitoring purposes. (Viholainen 2007, 31)

When motor's rotational speed and thus also the pump's rotational speed is reduced, the pump's efficiency stays close to nominal, especially if the systems static head is low. In high static head systems, the efficiency decreases more; depending on how good is the efficiency at nominal speed. On the other hand the motors efficiency is usually better when there is some load, compared to too small load. So the total efficiency could be better if there is some static head in the system. Figure 6 illustrates how the pump's operating point shifts when the rotational speed is reduced and how closely it follows the affinity parable.

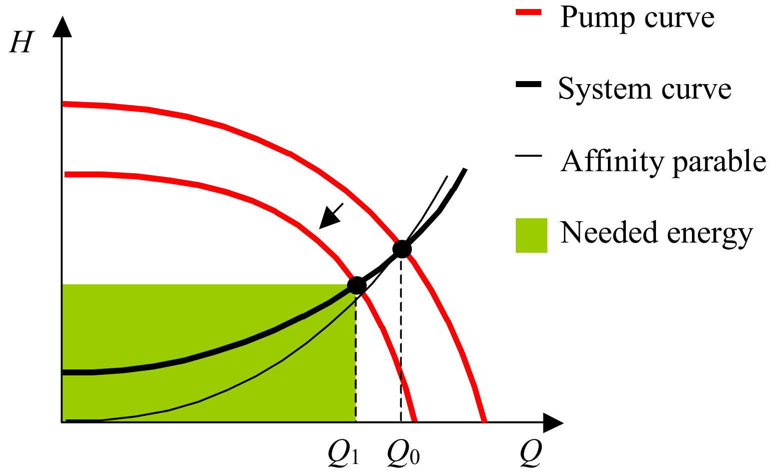

Figure 6. Affect of VSD control to pump curve and operating point.

Total efficiency of variable speed drive controlled pumping can be expressed with equation

$$\eta_{\mathrm{tot}} = \eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}}, \tag{16}$$

where

η_{d} Drive's efficiency

3. SQUIRREL CAGE MOTOR

Reasonable price, small maintenance costs, reliability and tolerance for different, often harsh, environments make squirrel cage motor one of the most popular motor types used in the industry. They are manufactured for powers ranging from 50 W to 10 MW. Rotational speed of a squirrel cage motor can be calculated with equation

$$n_\mathrm{r} = n_\mathrm{s}(1-s) = \frac{60 \cdot f}{p}(1-s), \tag{17}$$

where

n_r Motor's rotational speed [1/min]

n_s Synchronous speed [1/min]

p Number of pole pairs

s Motor's slip

Slip can be calculated from actual rotational speed with equation

$$s = \frac{n_\mathrm{s} - n_\mathrm{r}}{n_\mathrm{s}} \tag{18}$$

Large squirrel cage motors with power more than 11 kW have efficiency from 90 % to 96 %, depending on the number of pole pairs. Smaller ones have efficiency below 90 %. Above mentioned efficiencies are only valid at nominal load and at nominal rotational speed. Usually squirrel cage motors are air cooled, but those with power more than one megawatt can also be water-cooled. (Sarkomaa 1997, 8)

Structure of squirrel cage motor is simple and robust. Stator has three-phase winding and rotors winding is made of aluminum or more commonly copper bars, which are connected at each end with a ring. Bars aren't straight but have some skew to reduce noise and harmonics. Winding in rotor is called short circuit winding.

3.1 Motor losses and input power

Motor's nominal input power can be calculated from the values stamped on the motor's rating plate with equation

$$P_{\text{m,in(nom)}} = \sqrt{3}UI\cos\varphi\,, \tag{19}$$

where

U Nominal voltage [V]

I Nominal current [A]

$\cos\varphi$ Power factor of the motor

Nominal losses can be calculated by subtraction

$$P_{\text{nomloss}} = P_{\text{m,in(nom)}} - P_{\text{m,out}}\,, \tag{20}$$

when motor's mechanical power $P_{\text{m,out}}$, which is the motor's rated power, is known.

The following equations are only applicable when motor's nominal output power is 3…630 kW and the motor is standard IEC motor (50 Hz). The AC drive is assumed to be a voltage-source PWM frequency converter and the line voltage class must be "low voltage" i.e. less than 1000 V. There is many ways to divide the losses generated in the motor and this is only one of them.

To calculate needed input power with different speeds and loads motor losses must be estimated and new mechanical power must be calculated. Motor losses can be expressed with equation

$$P_{\text{motorloss}} = P_{\text{sinloss}} + P_{\text{harm}}\,, \tag{21}$$

where

$P_{\text{motorloss}}$ Losses generated in motor [kW]

P_{sinloss} Sine losses [kW]

P_{harm} Harmonic losses [kW]

Sine losses are formed of no-load dependent loss, speed dependent loss and load dependent loss and can be expressed with equation

$$P_{\text{sinloss}} = 0{,}2 \cdot P_{\text{nomloss}} + 0{,}15 \cdot \left(\frac{f}{f_{\text{nom}}}\right)^2 \cdot P_{\text{nomloss}} + 0{,}65 \cdot \left(\frac{T}{T_{\text{nom}}}\right)^2 \cdot P_{\text{nomloss}}, \tag{22}$$

where

f Variable speed drive's output frequency [1/s]

f_{nom} Nominal supply frequency [1/s]

T Motor's actual torque [Nm]

T_{nom} Motor's nominal torque [Nm]

Coefficients in the equation 22 are empirically determined for different loss types and are only valid with the restriction mentioned earlier.

Also the equation for harmonic losses is empirically determined and can be expressed with equation

$$P_{\text{harm}} = \frac{9}{f_{\text{sw}}} \cdot P_{\text{m,out}}, \tag{23}$$

where

f_{sw} Switching frequency of the VSD [1/s]

Mechanical power, $P_{\text{m,out}}$, can be calculated with equation 7, when the actual torque is known.

After calculating the motor losses and mechanical power the motor's input power can be expressed with equation

$$P_{\text{m,in}} = P_{\text{m,out}} + P_{\text{motorloss}} \tag{24}$$

(Efficiency Tool Version 1.0 User's Manual)

Based on theory figure 7 illustrates how motor's efficiency changes with the reduced drive frequency. Used motor on this example is the same as used on later measurements. Graph is drawn with motor's nominal torque of 98,8 Nm. Motor's nominal losses are 1,98 kW and used switching frequency is 3 kHz. Equations (19) – (24) were used on the calculations. In reality the motor could not be run with nominal torque at such small frequencies, because the cooling wouldn't be sufficient.

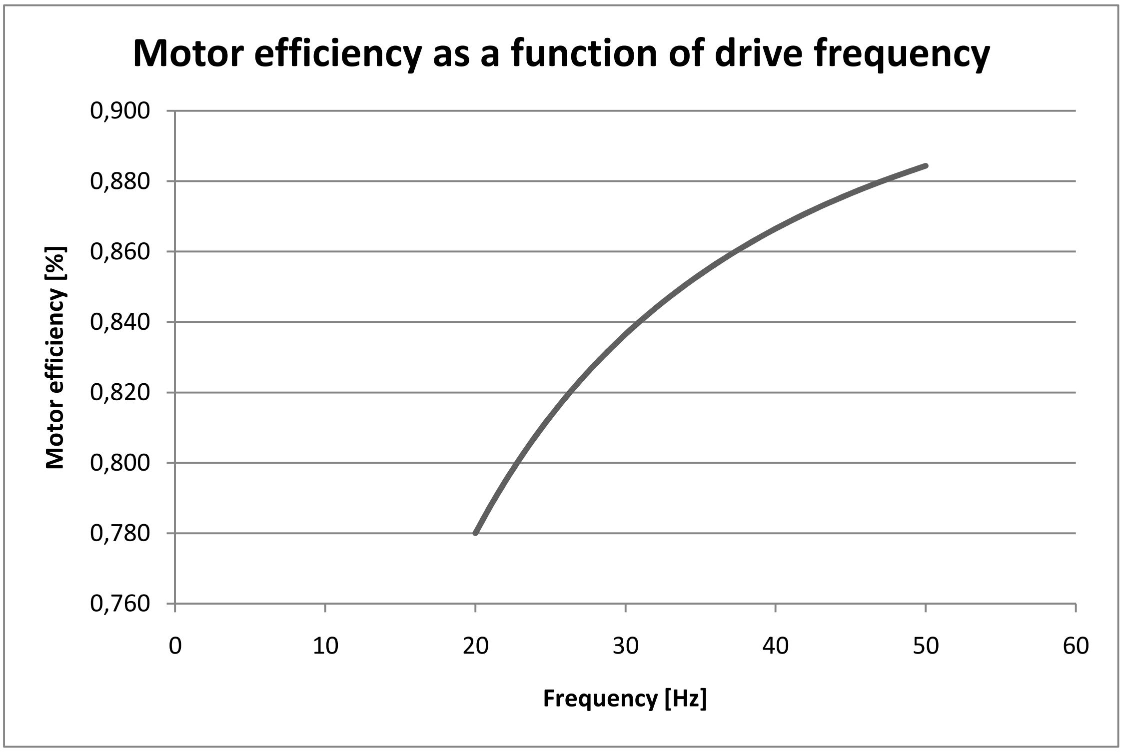

Figure 7. Motor efficiency as a function of drive frequency. Motor is the same as used on later measurements. Graph is drawn with motor's nominal torque of 98,8 Nm. Motor's nominal losses are 1,98 kW and used switching frequency is 3 kHz.

4. VARIABLE SPEED DRIVE

Variable speed drive's main function is to adjust the rotational speed of AC-motor by changing the frequency and voltage of the current fed into the motor. Using VSDs the strain in the supplying network can be reduced by smaller currents and smooth startups. Also the constant energy consumption can be reduced.

There are many different kinds of variable speed drives, but the one used on the measurements of this thesis uses intermediate circuit. The basic structure of a variable speed drive with intermediate circuit is illustrated in figure 8.

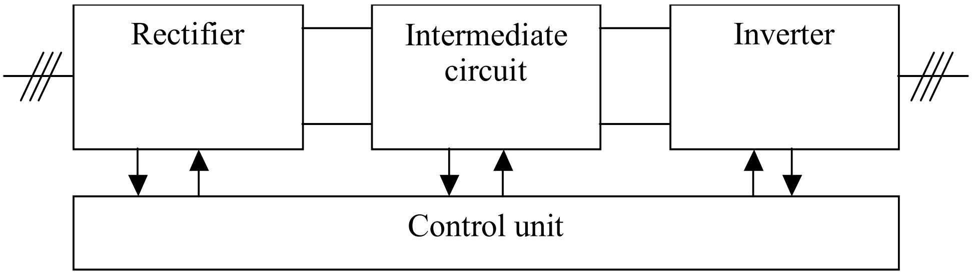

Figure 8. Basic structure of a variable speed drive with intermediate circuit as a block diagram.

Rectifier changes the alternate supply current into direct current. Rectifier can be simple diode bridge, controlled thyristor rectifier or active-front-end IGBT-bridge. Intermediate circuit, which separates rectifier and inverter, filters the rectified current. Intermediate circuit usually contains a capacitor bank, which stabilizes the dc-voltage. Inverter changes the direct voltage into alternate voltage and vice versa.

4.1 Drive losses and input power

The following equations are also only applicable with the same restriction as the equations representing the motor losses, which are that the motor nominal output power is 3…630 kW, motor is standard IEC motor (50 Hz), the AC drive is voltage-source PWM frequency converter and that the line voltage class is "low voltage" i.e. less than 1000 V. Again as is in representing equations for motor losses the following equations are only one way of representing drive losses.

To calculate nominal losses caused by the drive the nominal output power must be known first. It can be written as equation

$$P_{\mathrm{d,out(nom)}} = P_{\mathrm{m,in(nom)}} + P_{\mathrm{harm}}, \tag{25}$$

where

$P_{\mathrm{d,out(nom)}}$ VSD's nominal output power [kW]

Drive's nominal loss can then be calculated using drive's efficiency and nominal output power:

$$P_{\mathrm{d,nomloss}} = \frac{P_{\mathrm{d,out(nom)}}}{\eta_{\mathrm{d}}} \cdot (1 - \eta_{\mathrm{d}}) \tag{26}$$

where

$P_{\mathrm{d,nomloss}}$ Drive's nominal loss [kW]

η_{d} Drive's efficiency

Drive losses are divided into three parts: no-load dependent losses, speed dependent losses and load dependent losses. The weighting factors for different losses have been empirically derived and are only valid with the restrictions mentioned earlier. Drive losses can be written as equation

$$P_{\mathrm{d,loss}} = 0{,}35 \cdot P_{\mathrm{d,nomloss}} + 0{,}1 \cdot \left(\frac{f}{f_{\mathrm{nom}}} \right) \cdot P_{d,nomloss} + 0{,}55 \cdot \left(\frac{T}{T_{\mathrm{nom}}} \right) \cdot P_{\mathrm{d,nomloss}}, \tag{27}$$

where

$P_{\mathrm{d,loss}}$ Drive's losses at any given speed and load [kW]

It is noteworthy that the speed and torque ratios in equation (27) aren't in second power as they are in the equation (22) describing the motor losses. This is due to the different natures of electrical characteristics of dc-motor and frequency converter.

Drive's input power can now be expressed with equation

$$P_{\mathrm{d,in}} = P_{\mathrm{d,out}} + P_{\mathrm{d,loss}}, \tag{28}$$

where

$P_{d,in}$ Drive’s input power at any given speed and load [kW]

(Efficiency Tool Version 1.0 User’s Manual)

5. SPECIFIC ENERGY OF PUMPING

When cost of pumping needs to be calculated a useful measure is the specific energy E_s [kWh/m^3]. Also when comparing different system solutions the specific energy is a useful measure. (Europump and Hydraulic Institute p. 40-41)

In constant flow systems calculating the specific energy is a simple task by using the following equations. In systems where the flow rate varies each duty must be calculated separately and summated to obtain total costs. (Europump and Hydraulic Institute p. 40-41)

E_s is being calculated as a function of flow rate. Before this pump curves for variable speed operation and efficiency curves as a function of load and speed has to be obtained from manufacturers. (Europump and Hydraulic Institute p. 40-41)

To obtain the total operational cost the specific energy, E_s, for each duty needs to be combined with the duration diagram. After this different systems and regulation methods can be compared. (Europump and Hydraulic Institute p. 40-41)

$$Specific\ Energy\ (E_s) = \frac{Energy\ Used}{Pumped\ Volume} \tag{29}$$

$$E_s = \frac{P_{d,in} \cdot Time}{V} = \frac{P_{d,in}}{Q} \tag{30}$$

where

E_s Specific energy [kWh/m^3]

$P_{d,in}$ Drive's input power [kW]

Because E_s is a function of flow rate, it is necessary to evaluate this dependence. Systems with and without static head are separated due to their different characteristics. (Europump and Hydraulic Institute p. 40-41)

5.1 Systems without static head

The specific energy in systems without static head is dependent on the frictional head loss, which is produced by the losses in the pipe system, and on the efficiencies of the drive, motor and pump. (Europump and Hydraulic Institute p. 41)

The efficiencies of drive, motor and pump has to be evaluated for each duty point. Pump efficiency remains approximately the same in this kind of system when the speed is changed, but the drive and motor efficiencies can drop drastically as the load is reduced. Changing the system curve, by changing the setting of a valve, will change the duty point of the pump and also its efficiency. (Europump and Hydraulic Institute p. 41)

From equations (1), (16) and (30) we get:

$$E_s = \frac{Q \cdot H \cdot \rho \cdot g}{Q \cdot \eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}}} \tag{31}$$

Without static head, only dynamic head remains:

$$E_s = \frac{H_{\mathrm{dyn}} \cdot \rho \cdot g}{\eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}}} \tag{32}$$

5.2 Systems with static head

In systems with static head, the total head is comprised of static head, H_{st}, and dynamic head, H_{dyn}. The substitution $H = H_{\mathrm{st}} + H_{\mathrm{dyn}}$ will generate the following equations:

$$P_{\mathrm{d,in}} = \frac{Q \cdot (H_{\mathrm{st}} + H_{\mathrm{dyn}}) \cdot \rho \cdot g}{\eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}}} \tag{33}$$

$$E_{\mathrm{s}} = \frac{H_{\mathrm{st}} + H_{\mathrm{dyn}}}{H_{\mathrm{st}}} \cdot \frac{H_{\mathrm{st}} \cdot \rho \cdot g}{\eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}}} \tag{34}$$

if

$$\frac{H_{\mathrm{st}}}{H_{\mathrm{st}} + H_{\mathrm{dyn}}} = f_{\mathrm{HS}} \tag{35}$$

then

$$E_{\mathrm{s}} = \frac{H_{\mathrm{st}} \cdot \rho \cdot g}{\eta_{\mathrm{d}} \cdot \eta_{\mathrm{m}} \cdot \eta_{\mathrm{p}} \cdot f_{\mathrm{HS}}} \tag{36}$$

where

f_{HS} Hydraulic system factor

The different factors in equation (36) are all dependent of flow rate and are different for each duty point. When using variable speed drive they will vary with speed as the duty point moves along the system curve. (Europump and Hydraulic Institute p. 42)

Generally as the speed is reduced and the motor goes below 75 % of full load the motor efficiency will decrease. If the motor load drops below 50 % of full load the drop in motor and drive efficiency can be substantial. (Europump and Hydraulic Institute p. 42)

As we can see from equation (35) the hydraulic system factor will increase when the friction losses go towards zero. This happens when the duty point moves to left or when the friction losses are reduced. This leads to obvious conclusion that reducing the friction losses has a substantial effect on specific energy. (Europump and Hydraulic Institute p. 42)

/The specific energy will, however, always increase drastically as the duty point moves towards shut off head in systems with static head due to reduced pump, motor and drive efficiencies. In systems with high static head, this can happen even at a relatively moderate decrease in speed. / (Europump and Hydraulic Institute p. 42)

In systems with high static head the useful area of variable speed drive can be slightly improved by making sure that the system curve and the full speed pump curve intersect to the right of the pump's best efficiency point. (Europump and Hydraulic Institute p. 42)

By combining the information of specific energies at all operating points along the system curve with the information in flow duration diagram the cost of pumping can be calculated. (Europump and Hydraulic Institute p. 42)

6. ENERGY SAVING CALCULATION OF ACS850

This chapter introduces how ABB's new variable speed drive ACS850 calculates saved energy when using speed control instead of throttling control in pumping systems. Also the equations for calculating saved monetary amount and saved CO_2 emissions are being presented, even they are pretty obvious when saved energy is known.

The saved energy is calculated as follows:

$$E_{\text{saved}} = \int (P_{\text{m,in(nom)}} \cdot P_{\text{pump\%}} - P_{\text{m,actual}}) dt \,, \tag{37}$$

where

E_{saved} Saved energy [kWh]

$P_{\text{pump\%}}$ Pump power in percent [%]

The saved monetary amount is calculated as follows:

$$E_{\text{saved}}[\text{kWh}] \cdot \text{Energy price}[\text{price/kWh}] \tag{38}$$

The saved CO_2 emissions are calculated as follows:

$$E_{\text{saved}}[\text{MWh}] \cdot 0{,}5\text{ton/MWh} \tag{39}$$

These calculations are updated every 10 ms as long as the drive isn't stopped.

Motor's nominal power, $P_{\text{m,in(nom)}}$, pump power, $P_{\text{pump\%}}$, and energy price are parameters which user can change. Motor actual power, $P_{\text{m,actual}}$, is estimated by the VSD.

The 0,5 tons of CO_2 per MWh used in calculations is based on constant used by IEA (International Energy Agency). It is an average of different energy production alternatives. The average value is used because it cannot be known how the energy is being produced for the location where the VSDs are being used. It might be nice, if this parameter could be altered by the user when the user is sure how much CO_2 emissions is produced per MWh for example in the case where the industrial plant is producing its own energy with a certain method like for example burning peat.

Explaining equation (37) verbally it means that the energy saving is calculated from three different variables. These are nominal motor power inserted by the user, pump power as percentage of nominal motor power inserted by the user and estimated pump power, which is also axis power. First is calculated the constant pump power by multiplying the nominal motor power with the percentage representing the pump power. After this the estimated pump power is subtracted from the constant pump power. Finally this subtraction is integrated over time.

By analyzing this current energy saving calculation it can be noted that this method is based on the assumption that the axis power remains constant while the flow rate is changed by the throttling control. In reality this isn't the case and the axis power increases with the increased flow rate. Figure 9 illustrates pump's power curve and the assumption made on the calculation.

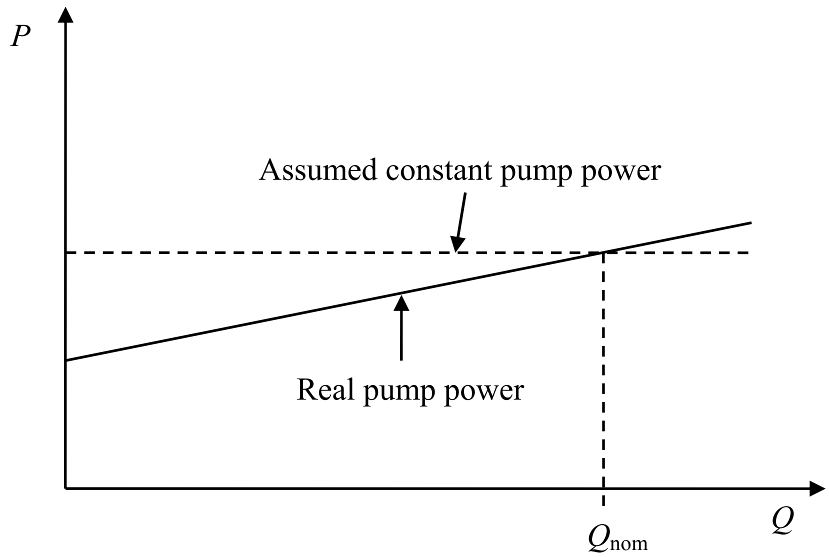

Figure 9. Figure illustrating the assumption made in the energy saving calculation. Solid line is real pump's power curve and dashed line is the assumed constant pump power.

Also this energy saving calculation is calculating the saved energy from mechanical powers and not from the electrical powers. It is likely that this will produce some error in the results. The estimated axis power used in the calculation is based on motor model used by the VSD and it should be fairly accurate.

7. MEASUREMENTS

On measurements powers consumed with two different control methods are measured, first with throttling control and then with VSD –control. After measurements the power used by the VSD –control is subtracted from the power used by the throttling control and the results are compared with the saved power calculated by the VSD.

7.1 Measuring equipment

The measuring equipment consists of:

- One power analyzer
- Variable speed drive
- Cage induction motor
- Torque transducer
- The pump, piping system and water tanks
- Venturi tube and ultrasonic flow meter for flow rate measurement
- Pressure meters in inlet and outlet of the pump

The used variable speed drive on the measurements is ABB ACS850-04-025A-5 with output power of 11 kW at no-overload use, the motor is Strömberg 15 kW 3-phase cage induction motor and the pump is G.A. Serlachius DC-80/260 centrifugal pump with 5 wing impeller diameter of 245 mm. More detailed list of measuring equipment is in appendix A.

Figure 10 illustrates the measuring equipment as a skeleton diagram for both, VSD control and throttling control of the pump.

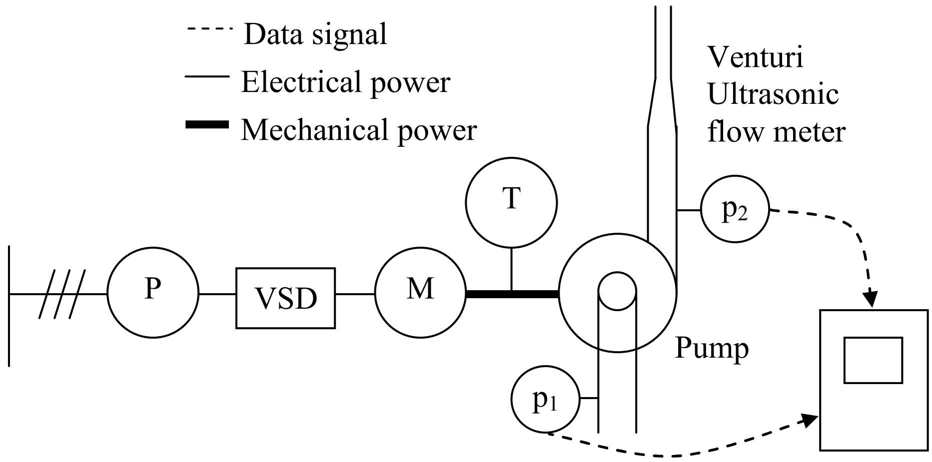

Figure 10. Used measuring equipment as a skeleton diagram for both measurements, throttling control and VSD control. At throttling measurement the VSD is running the motor at nominal (50 Hz) speed. There isn't any feedback from the system to the VSD. P stands for power analyzer, M for motor, T for torque transducer and p_1 and p_2 for pressure transducers in inlet and outlet of the pump.

In figure 10 the P stands for power analyzer, VSD for variable speed drive, M for motor, T for torque transducer and p for pressure meters. Power analyzer measures all three phases when measuring the input power and sums them into total input power. Venturi's pressure difference is measured as a voltage and then transformed into kilopascals and finally into flow rate. Also inlet and outlet pressure are measured as voltage and then transformed into millibars.

7.2 Course of the measurements

On the first measurement, where flow rate is controlled with throttling valve, input power and axis power are measured as well as the flow rate with venturi tube and ultrasonic flow meter. Motor input power and actual motor power is collected from the VSD. Also the pump's inlet and outlet pressures are measured for calculating the total head. In this measurement VSD drives the motor at nominal 50 Hz frequency.

On the second measurement, where motor is controlled with the VSD, input power, axis power and flow rate are measured, motor input power and actual motor power is collected from the VSD's parameters. Pump's inlet and outlet pressures are also measured like in the first measurement for calculating the total head.

7.3 Measurement results

As expected the measurement results did show that the current energy saving calculation of ACS850 gives clearly too large values for the saved energy. This was expected, because the calculation in ASC850 assumes that the axis power stays constant while the pump's outlet is throttled. Even from the pump's power -curves provided by the manufacturer can be seen that this isn't true.

At the beginning of the measurements, when using throttling control, it was noted that the measured axis powers didn't follow the pump's power curve provided by the manufacturer. In appendix B are presented the measured axis powers and their average plus linear fitting of the average axis power. For pump's reference power the new measured power at the nominal flow were used. If the power curve provided by the manufacturer would have been used, the energy saving calculation would have produced negative savings for the first few measurement points.

Also the calculated efficiencies are included in the measurement results. This is done for the sake of comparing these two flow control methods, and because the total efficiency of pumping could be a justified parameter to add in the VSD's parameter list. To support this, the following results will show that the total efficiency stays fairly constant while the pump is controlled by the VSD. This is interesting because the changes in total efficiency would indicate that there might be some kind of trouble in the pumping system, like for example clogging in the system. Also such parameter would help in tweaking the pumping system to its peak performance.

Each measured value in the results is an average of maximum and minimum value occurred at each measurement point.

The error margins in the results are calculated with various methods. Most of them are based on the error margins reported on the equipment manuals. Error margins of the error between real saved power and saved power and between real saved power and new saved power are determined with logarithmic derivation and total differential. Error margins of the efficiencies are calculated by adding the errors of the factors to the factors and thereby calculating the maximum values, from which the measured values are then subtracted, resulting the absolute error margins for the efficiencies. The error margins for the inlet and outlet pressure and total head are also determined with the same method, with the exception that those margins are relative meaning that they are divided by the measured values.

Example of calculating inlet pressure's error margin:

$$\frac{(V_{\text{inlet}} \cdot \Delta p \cdot \Delta V - 1)}{(V_{\text{inlet}} - 1)} - 1 = \frac{(2{,}576 \cdot 1{,}0025 \cdot 1{,}00041 + 2 \cdot 10\text{^-}3 - 1)}{(2{,}576 - 1)} - 1 \approx 0{,}60\,\%\,, \quad (40)$$

where

V_{inlet} Measured voltage from transducer

Δp Pressure transducer's error

ΔV Error in voltage measurement

Example of calculating total head's error margin:

$$\frac{p_{\text{outlet,max}} - p_{\text{inlet,max}}}{p_{\text{outlet}} - p_{\text{inlet}}} - 1 = \frac{3093 - 991}{3078 - 985} - 1 \approx 0{,}43\,\%\,, \quad (41)$$

where

$p_{\text{x,max}}$ Measured pressures added with error margins

Example of calculating real saved power's error margin:

$$\Delta P_{\text{m,in}} + \Delta P_{\text{d,in}} = 6\,\% + 6{,}6\,\% + 20\text{ W} = 12{,}6\,\% + 20\text{ W} \Rightarrow 13\,\% \quad (42)$$

Example of calculating error's absolute error margin:

$$\left(\left|\frac{\Delta P_{\text{saved}}}{P_{\text{saved}} - P_{\text{real saved}}}\right| + \left|\frac{\Delta P_{\text{realsaved}}}{P_{\text{saved}} - P_{\text{real saved}}}\right| + \left|\frac{\Delta P_{\text{realsaved}}}{P_{\text{real saved}}}\right|\right) \cdot |Error| = \left(\left|\frac{0{,}5}{0{,}14 - (-0{,}75)}\right| + \left|\frac{0{,}13}{0{,}14 - (-0{,}75)}\right| + \left|\frac{0{,}13}{-0{,}75}\right|\right) \cdot |-1{,}18| \approx 44\,\% \quad (43)$$

Because the manual of torque transducer was unavailable the measured torque was given the error margin of variable speed drives error margin for torque measurement. But as the results indicate the true accuracy of the used torque transducer could be significantly worse. Also because the used venturi tube is custom made it doesn't have manual and therefore the error margin for its flow measurement is estimated.

When calculating the flow rates measured by the venturi tube with equation (8), the variables used in the calculations are: $\rho = 1000\ \text{kg/m}^3$, $C_p = 0{,}98$, $D_0 = 0{,}15$ m and $D_1 = 0{,}1143$ m.

7.3.1 Results with throttling control

Below is a table of results in the first measurement when throttling control the flow rate.

Table 1. Results of throttling control measurement 1.1. Maximum flow rate of 76,3 m^3/h. Value $P_{m,out}$ is calculated from the measured torque and rotational speed. $P_{m,in}$ and $P_{m,actual}$ are parameters estimated by the used VSD. In theory $P_{m,out}$ and $P_{m,actual}$ should be the same, but there is difference caused by measuring error.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	76,29	69,48	992	3095	21,44
90 %	68,66	63,00	1009	3177	22,10
80 %	61,03	55,80	1025	3248	22,66
70 %	53,40	48,96	1036	3302	23,11
60 %	45,77	41,40	1048	3355	23,52
50 %	38,14	34,02	1058	3398	23,85
40 %	30,52	27,00	1065	3427	24,08
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,85	7,07	46,40	1483	7,21	7,25
90 %	7,47	7,00	44,20	1483	6,86	6,80
80 %	7,13	6,60	42,18	1484	6,55	6,34
70 %	6,82	6,40	40,35	1485	6,27	6,22
60 %	6,44	6,36	38,05	1485	5,92	5,88
50 %	6,06	5,79	35,70	1486	5,56	5,51
40 %	5,66	5,35	33,20	1486	5,17	5,13
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

In the first measurement, 1.1 and 1.2, the initial flow rate have been tried to put to the pump's best operation point. Below in table 2 are the efficiencies calculated from the measurement 1.1. The expected pump efficiency should have been over 70 %, but as it can be seen from the η_p-columns it wasn't quite hit or there is some error in the measurement. Like for example that the flow rate measured by the venturi tube isn't what it really is. One option is also that the manufacturer's pump curves don't apply anymore for the pump in use for some reason. This is very likely, because the used pump is very old.

The over 100 % values in the motor efficiencies are likely caused by measuring error. When taking into account the error margin of 12 % the 102 % efficiency could be anything between 90 % and 114 %. It is also likely that the torque measurement has even worse accuracy as estimated in table 1. The biggest reasons for such peculiar motor and drive efficiencies are probably inaccurate motor input power, $P_{m,in}$, estimation and/or wrongly selected values from the largely fluctuating VSD-parameters. Usually 15 kW induction motor has at 50 % load an efficiency of 86–92 %.

Table 2. Efficiencies calculated from the throttling measurement 1.1. Maximum flow rate of 76,3 m^3/h. The error margins in this table are absolute values, not percentages of measured efficiencies.

	Efficiencies										
	Total efficiency		$\eta_m\eta_p$		η_d	η_m		η_p			
								Venturi		Ultrasonic	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	56,8 %	51,7 %	63,1 %	57,4 %	90,1 %	102,0 %	102,5 %	61,8 %	61,5 %	56,3 %	56,0 %
90 %	55,3 %	50,8 %	59,1 %	54,2 %	93,7 %	98,1 %	97,1 %	60,2 %	60,8 %	55,3 %	55,8 %
80 %	52,9 %	48,3 %	57,1 %	52,2 %	92,6 %	99,3 %	96,0 %	57,5 %	59,5 %	52,6 %	54,4 %
70 %	49,3 %	45,2 %	52,5 %	48,2 %	93,8 %	98,0 %	97,2 %	53,6 %	54,1 %	49,1 %	49,6 %
60 %	45,6 %	41,2 %	46,1 %	41,7 %	98,8 %	93,0 %	92,5 %	49,6 %	49,9 %	44,8 %	45,1 %
50 %	40,9 %	36,5 %	42,9 %	38,2 %	95,5 %	96,0 %	95,2 %	44,6 %	45,0 %	39,8 %	40,2 %
40 %	35,4 %	31,3 %	37,5 %	33,1 %	94,4 %	96,7 %	95,9 %	38,8 %	39,1 %	34,3 %	34,6 %
Error margins:	± 6,0 %	± 4,9 %	± 6,1 %	± 4,9 %	± 13,7 %	± 11,9 %	± 12 %	± 5,2 %	± 5,2 %	± 4,2 %	± 4,1 %

In figure 11 are the total efficiencies of throttling measurement 1.1. The total efficiency in this case is the combined motor-pump efficiency and the numerical values are in table 2 at "$\eta_m\eta_p$"–columns.

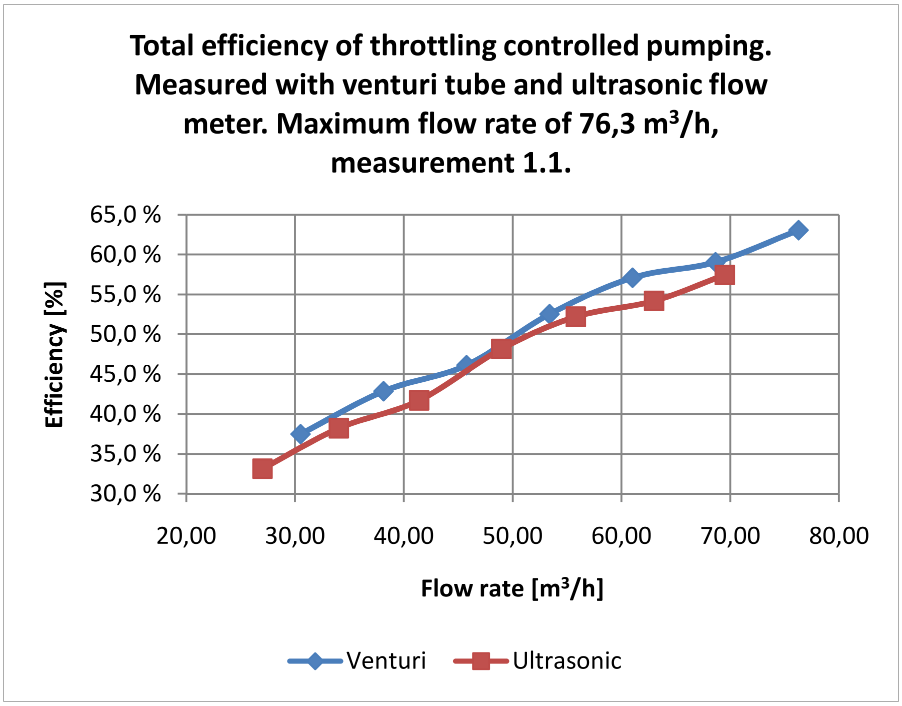

Figure 11. The total efficiencies of throttling measurement 1.1. Motor-pump efficiencies. The line called "Venturi" is calculated from the venturi tube's flow rate measurements and the line called "Ultrasonic" is calculated from the ultrasonic flow rate measurements.

The difference between the efficiencies calculated from the venturi tube's flow rate measurement and from the ultrasonic flow rate measurement is noticeable and it cannot be said which one is more reliable. Smaller error margin of the ultrasonic flow meter would suggest that efficiencies calculated from its flow rate measurements are more reliable.

From table 2 it can be seen that the efficiencies have quite large error margins and the differences between efficiencies of those two flow rate measurements are mostly inside these margins.

Rest of the results of throttling control measurements are in appendix C.

7.3.2 Results with VSD control

Below in table 3 are the measuring results of VSD controlled pumping, measurement 1.1. In table 4 are the efficiencies calculated from the same measurement. And in figure 12 are the efficiencies as a graph.

Table 3. Results of VSD controlled pumping, measurement 1.1. Maximum flow rate of 76,3 m^3/h. $P_{m,out}$ is calculated from the measured torque and rotational speed. In theory $P_{m,out}$ and $P_{m,actual}$ should be the same. $P_{m,in}$ and $P_{m,actual}$ are parameters estimated by the used VSD.

	Flow rate		Pressure		Total head	
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**	
100 %	76,29	70,56	985	3078	21,34	
90 %	68,66	62,64	1004	2735	17,65	
80 %	61,03	56,16	1019	2454	14,63	
70 %	53,40	48,96	1034	2213	12,02	
60 %	45,77	41,40	1047	1992	9,63	
50 %	38,14	34,67	1058	1813	7,70	
40 %	30,52	27,43	1068	1659	6,03	
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %	
	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,82	7,35	46,00	1482	7,14	7,03
90 %	5,80	5,37	37,80	1335	5,28	5,13
80 %	4,28	3,90	30,95	1200	3,89	3,71
70 %	3,09	2,84	25,00	1070	2,80	2,69
60 %	2,12	1,83	19,60	935	1,92	1,73
50 %	1,43	1,22	15,28	810	1,30	1,14
40 %	0,93	0,74	11,65	685	0,84	0,68
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

The axis powers calculated from the measured torque and speed gives different values than the axis power estimated by the VSD. These results in differences between pump efficiencies calculated from them. Also differences between flow rates measured with venturi tube and ultrasonic flow meter results in differences between efficiencies calculated from these values.

Table 4. Efficiencies calculated from VSD controlled pumping, measurement 1.1. Maximum flow rate of 76,3 m^3/h. As well as in table 2 the error margins in this table are absolute values and not percentages of the measured efficiencies.

	Efficiencies											
	Total efficiency		**$\eta_m\eta_p$**		**η_d**	**η_m**		**η_p**				
								Venturi		**Ultrasonic**		
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	
100 %	56,8 %	52,5 %	60,4 %	55,9 %	94,0 %	97,2 %	95,7 %	62,1 %	63,1 %	57,5 %	58,4 %	
90 %	57,0 %	52,0 %	61,5 %	56,1 %	92,6 %	98,5 %	95,5 %	62,5 %	64,4 %	57,0 %	58,8 %	
80 %	56,9 %	52,4 %	62,5 %	57,5 %	91,1 %	99,9 %	95,3 %	62,6 %	65,6 %	57,6 %	60,4 %	
70 %	56,6 %	51,9 %	61,7 %	56,5 %	91,7 %	98,8 %	94,9 %	62,4 %	65,0 %	57,2 %	59,6 %	
60 %	56,8 %	51,4 %	65,8 %	59,5 %	86,3 %	105,2 %	94,5 %	62,6 %	69,6 %	56,6 %	63,0 %	
50 %	56,2 %	51,1 %	65,9 %	59,9 %	85,3 %	106,6 %	93,4 %	61,8 %	70,5 %	56,2 %	64,1 %	
40 %	54,2 %	48,7 %	67,7 %	60,9 %	80,0 %	112,9 %	91,2 %	60,0 %	74,2 %	53,9 %	66,7 %	
Error margins:	± 7,0 %	± 5,7 %	± 6,5 %	± 5,2 %	± 13,1 %	± 13,2 %	± 11,2 %	± 5,3 %	± 6,3 %	± 4,2 %	± 4,9 %	

As I mentioned earlier, the total efficiency stays quite flat across the all measurement points. In figure 12 the numerical values of total efficiencies are taken from “Total efficiency” –columns of table 4. Table 4 also contains over 100 % efficiencies, which are likely produced by measuring error. Large error margins sparsely explain them. When looking figure 7 in chapter 3.1 illustrating the motor efficiency as a function of drive frequency, it can be noted that motor's efficiency should decrease with decreasing frequency and that the measured efficiencies are clearly higher than the calculated efficiencies with nominal load. Theoretically the efficiencies should be even worse than those on the figure 7, because the motor's load on the measurements is about 50 %.

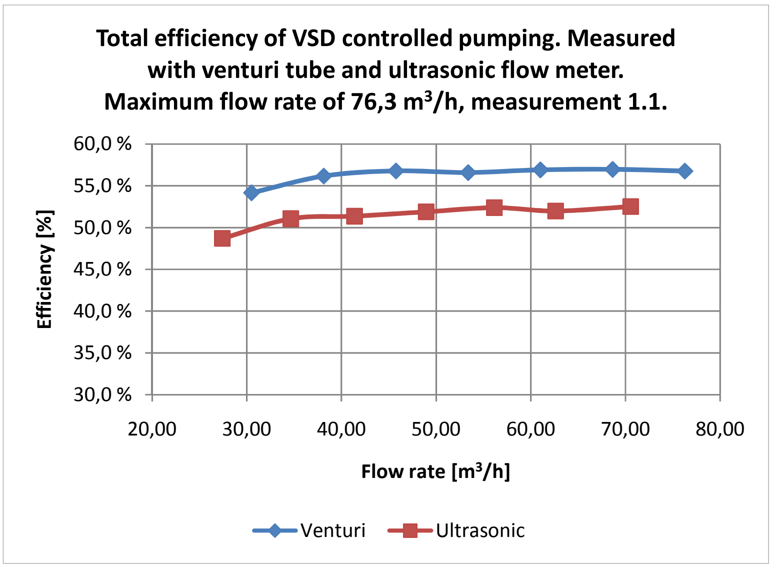

Figure 12. Efficiencies calculated from VSD controlled pumping measurement 1.1. The line called "Venturi" is calculated from the venturi tube's flow rate measurement and the line called "Ultrasonic" is calculated from the ultrasonic flow rate measurements. Differences between efficiencies calculated from these two flow rate measurements are mostly inside the error margins. Compared to throttling control the efficiency stays fairly constant.

In appendix D are the rest of the measurement results when VSD controls the flow rate.

7.4 Result summary and analysis

In this chapter is presented the summary and analysis of the combined results which include the calculation results for saved energy, real saved energy and for the relative error between them. Also figures illustrating *QH*-curves and *QP*-curves are included in this chapter.

In table 5 are calculated results of measurement 1.1. for saved power, real saved power and for the relative error between them. Saved power is calculated with equation (37) without integration. Real saved power is calculated from subtraction of $P_{m,in}$ of the related measuring point of throttling controlled pumping and P_{in} of the VSD controlled pumping. The error is calculated with the following equation:

$$Error = \left(\frac{Saved\ Power}{Real\ saved} - 1 \right) \cdot 100\% \tag{44}$$

Table 5. Saved power, real saved power and relative error between them. Maximum flow rate of 76,3 m^3/h. Measurement 1.1. The error margins are percentage of measured values expect for the error margins of error, which are absolute values meaning that for example -118 % error could be anything between -162 % and -74 %.

Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	76,29	0,14	-0,75	-118 %	± 44 %
90 %	68,66	2,04	1,21	69 %	± 22 %
80 %	61,03	3,46	2,33	49 %	± 10 %
70 %	53,40	4,48	3,31	35 %	± 6,8 %
60 %	45,77	5,44	4,25	28 %	± 5,1 %
50 %	38,14	6,03	4,36	38 %	± 5,3 %
40 %	30,52	6,49	4,42	47 %	± 5,4 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗

In figure 13 is a graph drawn from the table 5 presenting the saved power, real saved power, absolute and the relative error between.

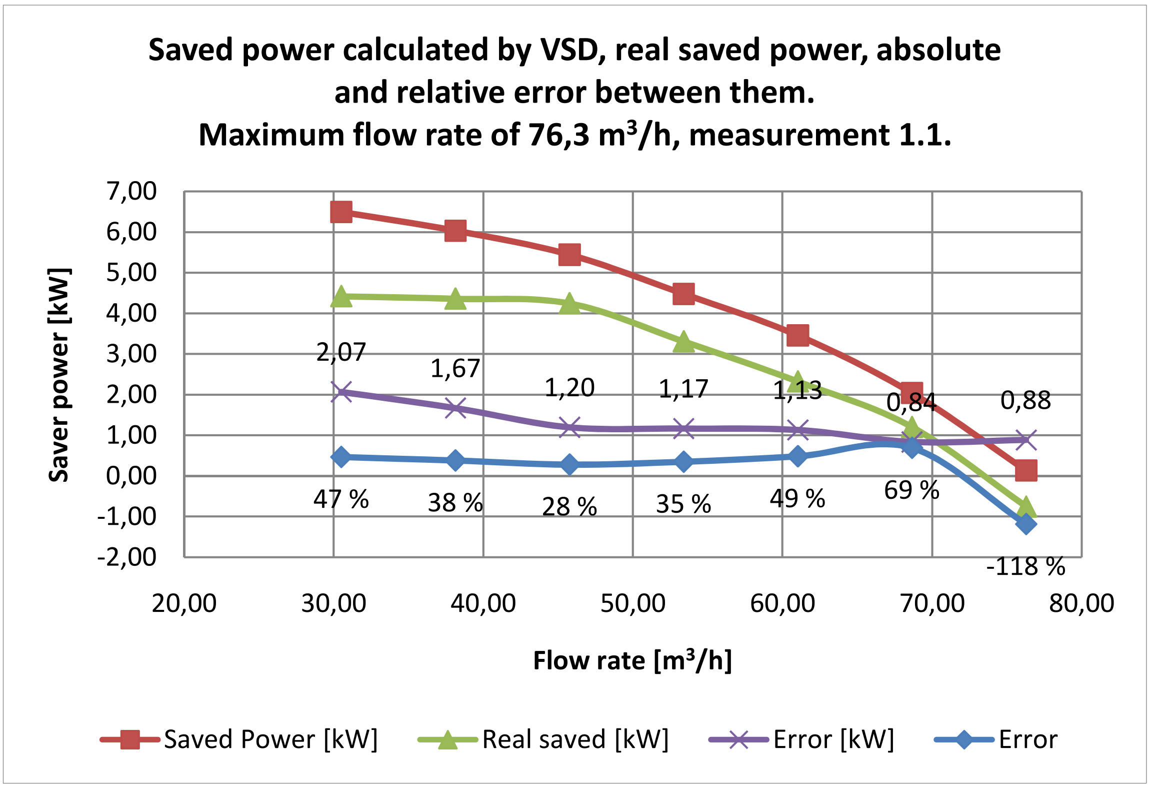

Figure 13. Saved power, real saved power, absolute and the relative error between them. Measurement 1.1 at maximum flow rate of 76,3 m^3/h. The errors in calculated saved powers are significant. The last two error values on the right have such large error margins that they might be considered unreliable.

As it can be seen from table 5 and figure 13 the error in saved power calculated by the same method, which the ACS850 uses, is quite significant. Even if the error margins for the real saved power and for the error itself are pretty large, it is obvious that the current energy saving calculation in ASC850 gives significantly too large values for the saved energy. In appendix E are the rest of the results for saved power calculations.

In figure 14 below are the measured pump and systems curves from measurement 1.1 together with the pump curve provided by the manufacturer reduced to 1485 rpm.

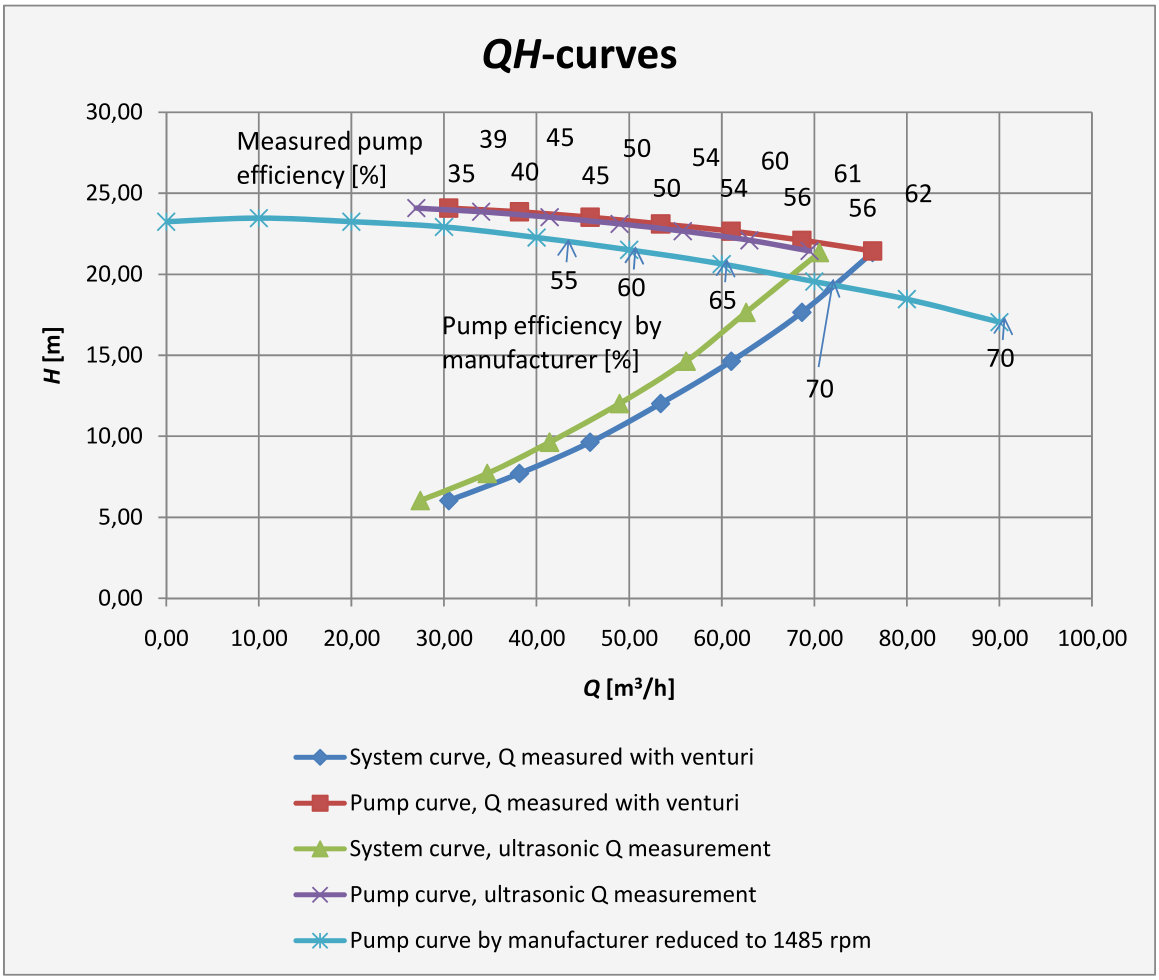

Figure 14. *QH*-curves of the measurement 1.1. Measured pump's head curves, measured system curves and manufacturer's pump curve reduced to 1485 rpm. Measured pump curves are higher than the pump curve provided by the manufacturer, which means that the pump is generating more head than the pump curve by manufacturer would suggest.

In figure 15 are the measured *QP*-curves together with the *QP*-curve provided by the manufacturer reduced to 1485 rpm.

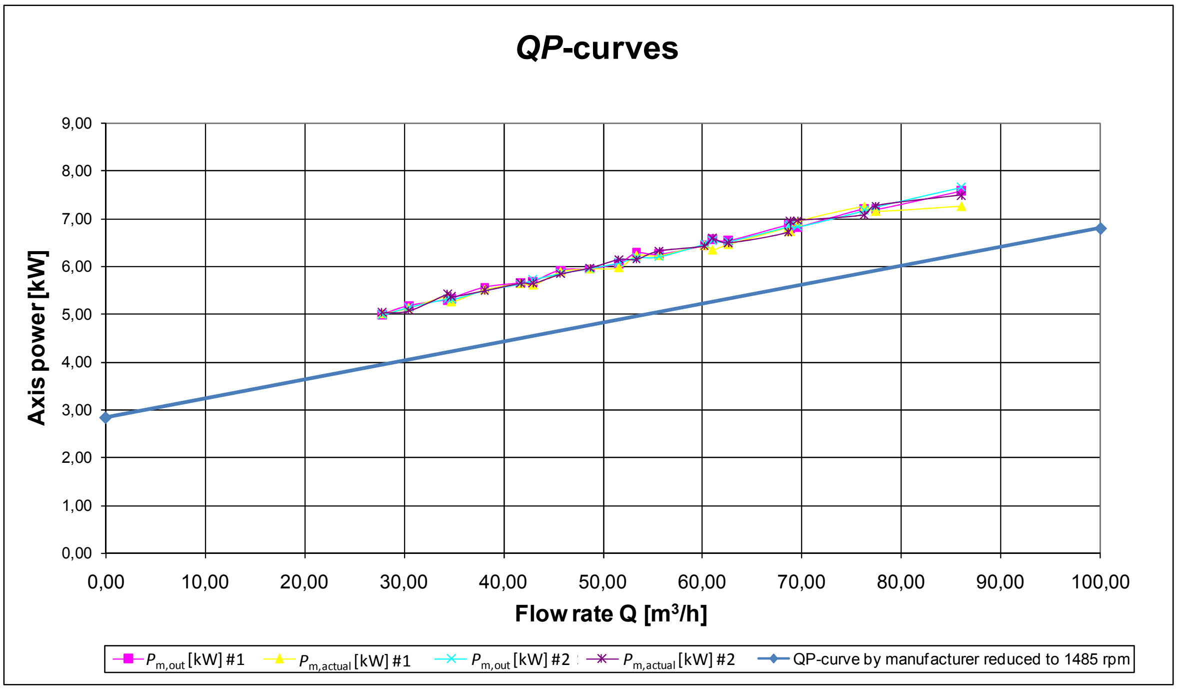

Figure 15. Measured pump's power curves together with the power curve provided by the manufacturer reduced to 1485 rpm. #1 and #2 means first and second measuring pass.

The approximately 1 kW higher measured pump's power curves compared to power curve by the manufacturer could be explained by the higher head production of the pump together with the poorer pump efficiencies compared to those provided by the manufacturer. Smooth measured pump and system curves in figure 14 suggest that the precision of the measurements is good. If there is some error on the measurements, it is probably systematic. The over 160 mbar difference between pump's inlet and outlet pressures while the pump was stopped, probably led to some sort of systematic error on the measurements. This would for example mean that the 24 m point on the pump curve would be at 22,4 m. So in reality the measured pump curve could be closer to the one provided by the manufacturer. This 160 mbar difference has also affect on the pump and total efficiencies.

8. IMPROVEMENT AND NEW ENERGY-EFFICIENCY PARAMETERS

This chapter contains a proposal for improvement to the current energy saving calculation and proposals for new energy-efficiency parameters to add in the VSD's parameters.

8.1 Proposal for improvement in energy saving calculation

In this chapter is presented a proposal for an improvement in energy saving calculation of the ACS850. The improvement requires that the flow rate is measured somehow and fed into the VSD's parameters. Also two more parameters are required for calculating the axis power from the flow rate. These are the multiplier and the constant of the linear fitting of the pump's power curve.

Equation (45) presents the form of linear fitting of pump's power curve.

$$P(Q) = Q \cdot \mathrm{M} + \mathrm{C}, \tag{45}$$

where

P Pump's axis power [kW]

Q Flow rate [m^3/h]

M Multiplier [kWh/m^3]

C Constant [kW]

The multiplier M = 0,04347 kWh/m^3 and the constant C = 3,82571 kW are used for calculating the new axis powers when calculating the new saved powers. The linear fitting is the same as the one derived from the average axis powers from the throttling measurements. It is presented in the graph of appendix B.

The method for calculating the saved power is the same as currently in ACS850 except that the pump's axis powers are calculated from the measured flow rates with the equation (45) which describes the linear fitting of the axis powers of throttling control.

The best results for energy saving calculation would be achieved, if the linear fitting of axis power would be calculated from the axis powers estimated by the VSD when the pump is throttling controlled. This can be easily done after the VSD is assembled for use with the pump and by collecting the axis powers from the VSD's parameters while the pump is throttling controlled as if the pump would still be controlled with this old control method.

In table 6 are the results of newly calculated saved power, real saved power and the relative error between them.

Table 6. Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 76,3 m^3/h, measurement 1.1. The error margins are percentage of measured values expect for the error margins of new error, which are absolute values meaning that for example the 40 % error could be anything between 31 % and 59 %.

Flow rate		**Saved power**			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	76,29	0,11	-0,75	-115 %	± 44 %
90 %	68,66	1,69	1,21	40 %	± 19 %
80 %	61,03	2,77	2,33	19 %	± 8,9 %
70 %	53,40	3,46	3,31	4,5 %	± 5,6 %
60 %	45,77	4,09	4,25	-3,6 %	± 4,4 %
50 %	38,14	4,35	4,36	-0,3 %	± 4,2 %
40 %	30,52	4,48	4,42	1,3 %	± 4,1 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗

In figure 16 is a graph drawn from table 5 and table 6 which shows newly calculated saved power, saved power and real saved power and the relative errors between saved power versus real saved and new saved power versus real saved.

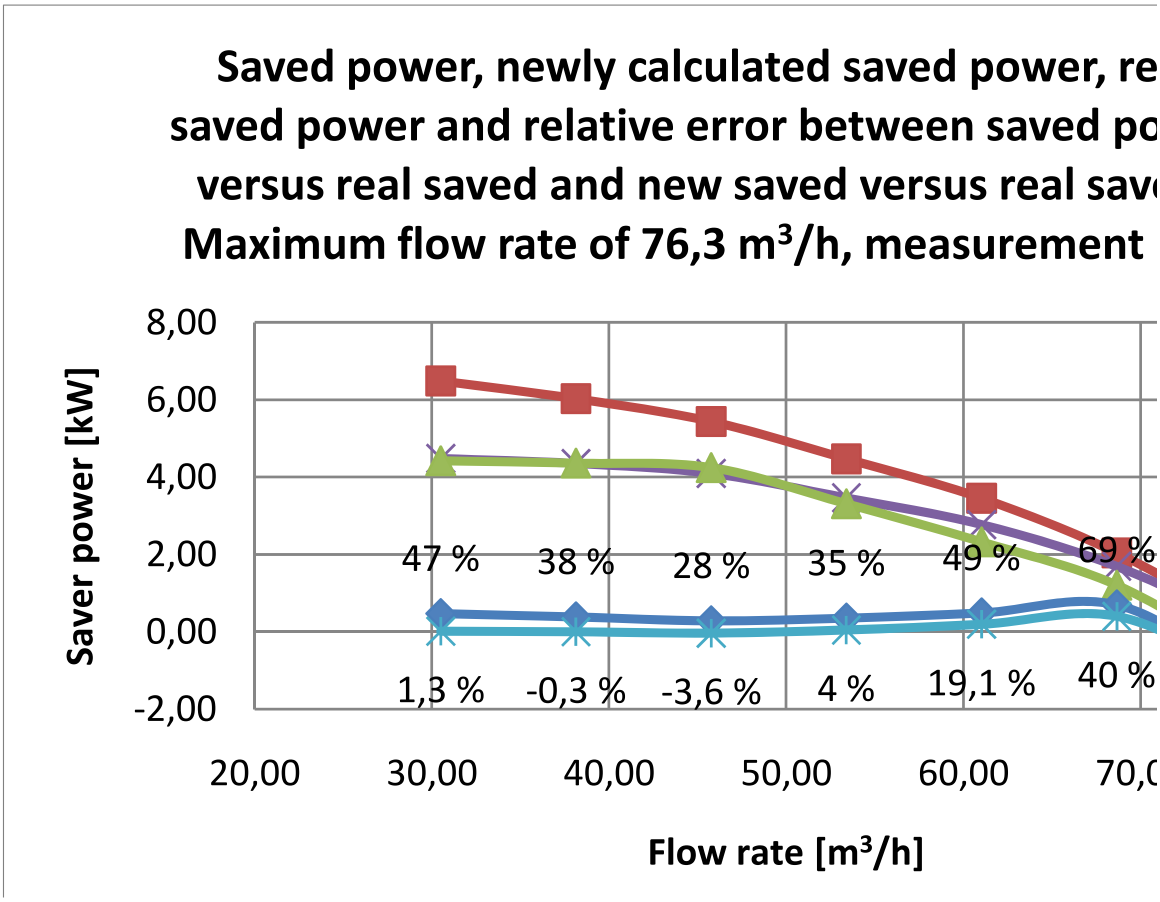

Figure 16. This figure illustrates newly calculated saved power, real saved power and relative error between them. The saved power and error are added for making the comparison between new and old calculation easier. Maximum flow rate of 76,3 m^3/h, measurement 1.1.

As it can be seen from table 6 and from figure 16 the new method for calculating the saved power, and energy, would work much better than the current calculation, at least when the flow rate is reduced significantly from the nominal, meaning that the motors rotational speed is reduced significantly.

The greater error, when pump's rotational speed has been reduced only little might be due to the fact that the saved power is calculated from the mechanical and not from the electrical powers.

It must be also noted that the errors in saved power has less impact the more right they are on the graph, because the saved powers are smaller there, reducing eventually to zero. This is why the error's on left have more impact on how much error is produced to the saved energy calculation. This of course also depends on how the rotational speed is reduced. For example if the rotational speed is reduced only little, the error in calculated saved energy is large, but when the rotational speed is reduced more, the error gets smaller and also the saved energy increases faster, thus reducing the overall error. Rest of the results of newly calculated saved powers are in appendix F.

8.2 Proposals for new energy-efficiency parameters

In this chapter are presented few proposals for new parameters to add in the VSD's parameters, which might tell the user how efficient their variable speed drive system is and might also help in tweaking the system or indicate changes in the system performance.

It was already suggested that the total efficiency could be a justified add in the VSD's parameters, but it doesn't come without effort, because if calculated as it has been done in this chapter, measurements in the system must be done. Input power of the VSD would need to be somehow estimated or measured. Also the inlet and outlet pressures of the pump would need to be measured as well as the flow rate would need to be measured or estimated. Also the calculation of total head, which is required for calculating the hydraulic power, would require that the inlet and outlet pipes diameters are either the same or they are fed into to the VSD and also the inlet and outlet pressure transducers difference in altitude must be either the same or fed into the VSD for the calculation to be possible.

The total efficiency of pumping can be calculated with the following equations:

$$\eta_{\text{total}} = \frac{\rho \cdot g \cdot Q \cdot H}{P_{\text{in}}} \tag{46}$$

$$H = \frac{p_{\text{outlet}} - p_{\text{inlet}}}{\rho \cdot g} + \frac{v_{\text{outlet}}^2 - v_{\text{inlet}}^2}{2g} + k\,, \tag{47}$$

where

v Speed of flow [m/s]

k Pressure transducers difference in altitude [m]

$$v_{\text{outlet}} = \frac{Q}{A_{\text{outlet}}},\ v_{\text{inlet}} = \frac{Q}{A_{\text{inlet}}} \tag{48, 49}$$

$$A_{\text{outlet}} = \pi \cdot \left(\frac{D_{\text{outlet}}}{2} \right)^2, A_{\text{inlet}} = \pi \cdot \left(\frac{D_{\text{inlet}}}{2} \right)^2 \qquad (50, 51)$$

Specific energy of pumping could be calculated with equation (30) without the need of measuring inlet and outlet pressures. Only input power and flow rate is required for the calculation. This would show how much energy is used per pumped cubic meter at each operating point and would make the annual cost calculation easy with the help of flow duration diagram.

9. ENERGY SAVING ESTIMATION OF OTHER SYSTEMS

The same principle of energy saving estimation might be possible to use on other pump and fan applications. Estimating the saved energy compared to other control methods. User could then select the older control method for comparison in the VSD’s parameters. Possible comparison targets could be hydraulic clutch or gearbox as well as in fan applications the outlet damper. It might be also possible to estimate the energy saving compared to other control methods in electric drive systems. Like for instance the gearbox and different clutches.

Energy saving estimation wouldn’t always need to involve VSDs and electric drives. For example it could be done on computers and estimate the saved energy with different energy saving modes, like when the processor frequency is decreased or display is dimmed. Same kind of function could be implemented on various domestic appliances or home electronics. One example could be laundry and dishwashing machines. The laundry machine or dishwasher could display the saved energy when using lower temperature, slower spin or shorter program. Also this could be implemented on can driers. One example could be also a coffee machine, which shows how much energy is saved when the heating plate’s temperature is set to lower setting.

Electric cars and why not also usual cars could also tell on their displays how much energy is saved when driving on reduced speeds. Can’t be known how practical it would be, because people don’t usually have much of choice to select their own speed when driving a car. But maybe they wouldn’t break the speed limits so often, if they would know how much money they can save by obeying them. On the other hand there is usually only one optimal speed and optimal gear selection for optimal fuel consumption. Also many new cars already show how much fuel is consumed per kilometer or mile. This function could be extended with statistical functions which would show the average fuel consumption of selected time frame, like for instance for the last year or for the last trip. The fuel consumption could also be displayed as energy in kilowatt-hours and as estimate of released CO_2 gasses as metric tons. It is obvious that the driving style has a great effect on how much fuel is consumed while driving. Fiat has developed a software called “eco:Drive”, which analyses driving style and helps to make it more efficient. Memory-stick attached to usb-port of “Blue&Me”-system in car will collect all the information related to driving style and after an appropriate driving session data can be fed into “eco:Drive”-software on a computer for analysis. “Eco:Drive”-software gives a clear presentations of the driver’s driving style and the ways it could be improved. Progress can be monitored with an “eco-index” given by the software, which reflects how economic the driving has been. Fiat claims that by using the tips given by this software driving style could be made up to 15 % more efficient.

10. SUMMARY

As for conclusion it be can be said that energy saving is a very hot topic and all methods of motivating the end users to save energy are worth of developing. This wouldn't only bring more income for the developers, but would also influence our economy and environment positively.

As the measurements indicate the current energy saving calculation of ACS850 gives significantly too large values for the savings. This would require more development and possibly even totally different method of calculating the saved energy apart from the improvement suggested in chapter 8.1.

After considering all the possibilities, there is a conclusion that the saved energy of VSD controlled pumping versus throttling controlled pumping cannot be done without some feedback from the system. The current method is simple and requires minimal input from the user, but doesn't give accurate results.

The initial objectives of this thesis included also some sort of competitor comparison, but this wasn't included in the thesis, because it didn't really belong to the scope of this thesis and also because acquiring the needed information might have been quite difficult. All in all the objectives of this thesis were quite well met except that the focus was more on the measurements and not on the energy-efficiency part, but this isn't necessary a bad thing.

The meaning of the results in this thesis is that there is still space for improvement in the current energy saving calculation. The next step might be to test how much the proposed improvements would really improve the energy saving calculation and if they are too complex to implement or not.

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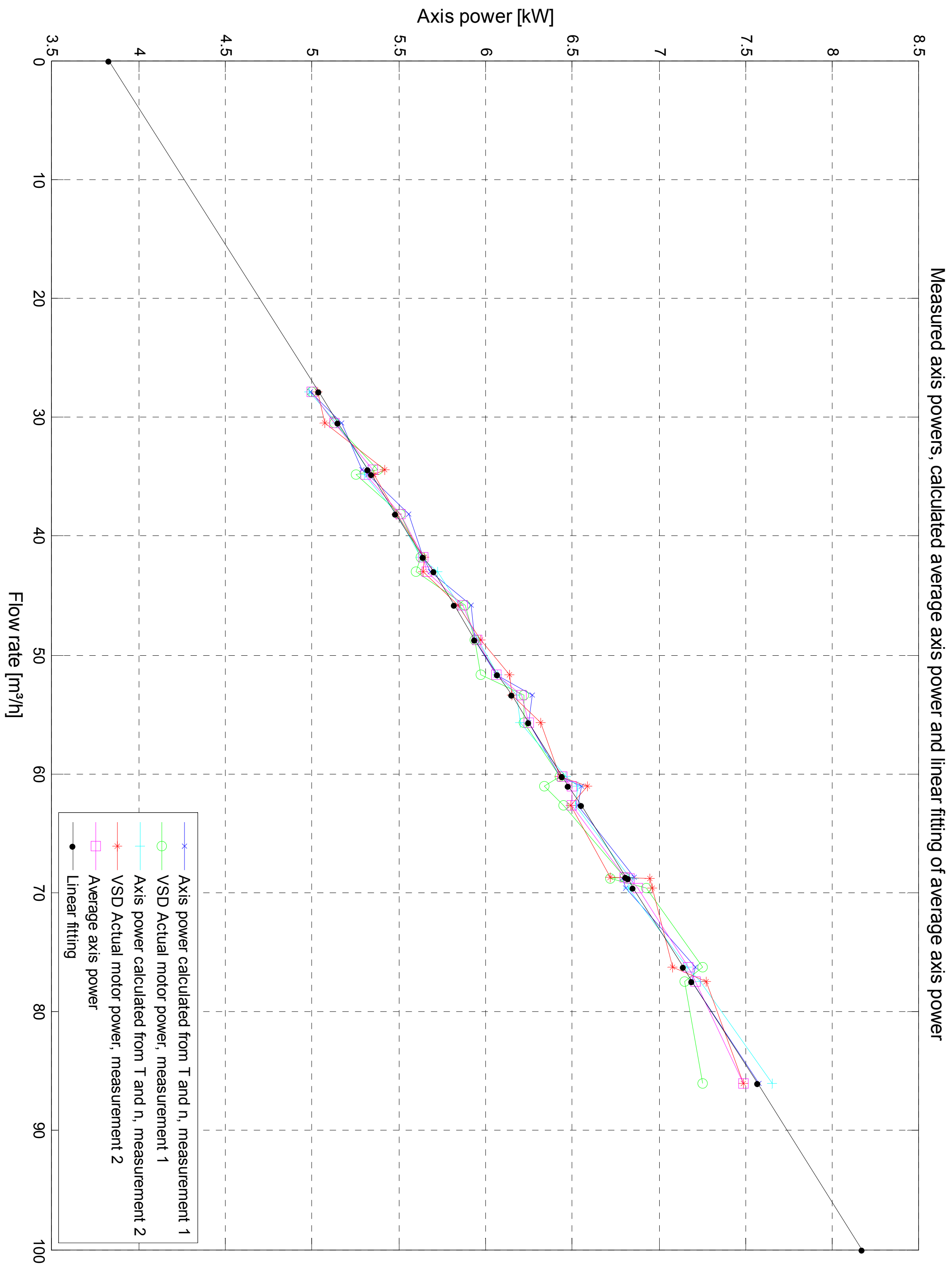
- Variable speed drive:
  - Voltage-source PWM frequency converter
  - ABB ACS850-04-025A-5
  - Nominal input current: 20 A
  - Nominal output current 25 A, Max: 33 A
  - No-overload use: 11 kW
  - 380 … 500 V AC +10%/-15%, 3-phase
  - 50 … 60 Hz ±5%
- Cage induction motor:
  - Strömberg
  - 50 Hz, 15 kW, 380 V, 30 A, 3-phase, 1450 rpm
  - $\cos\varphi$ = 0,86
- Centrifugal pump:
  - G.A. Serlachius Oy
  - DC-80/260, 1425 rpm, z = 5
  - Impeller diameter/width: 245/25 mm
- Power analyzer:
  - Fluke 1735 Power Logger Analyst
- Venturi, pump inlet and outlet pressure measurement:
  - Fluke Hydra Data Acquisition unit
  - Pressure transducers
    - Venturi: Valmet
      - Calibrated 21.11.2008
    - Inlet: Druck PTX 1400
    - Outlet: Rosemount E1151
      - Calibrated 21.04.2008
- Ultrasonic flow meter:
  - Controlotron System 1010 Uniflow
- Torque transducer:
  - ABM Drehmoment Messwelle T3FN
  - ABM MZ 3558, Measuring unit
  - ABM DA 3418, Display unit

Appendix B: Measured axis powers, average axis power and its linear fitting



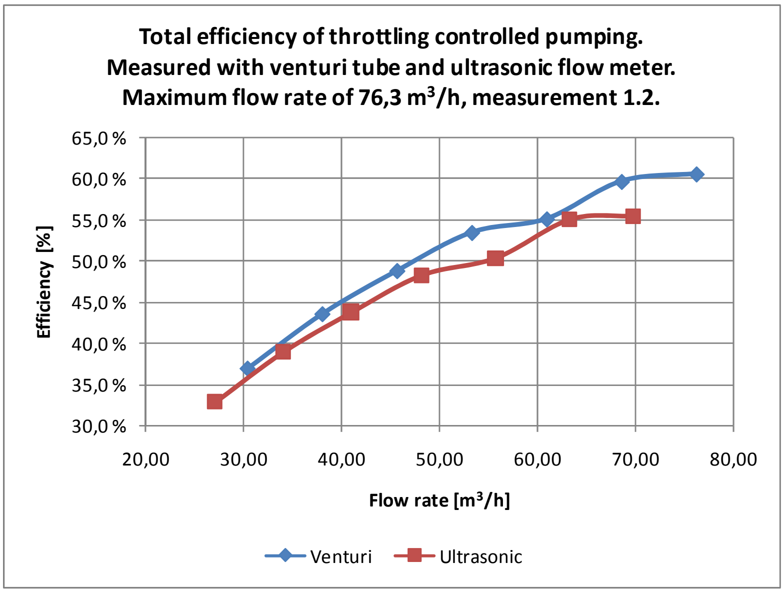
Results of throttling control measurement 1.2. Maximum flow rate of 76,3 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	76,29	69,84	984	3079	21,35
90 %	68,66	63,36	1001	3155	21,96
80 %	61,03	55,80	1017	3235	22,61
70 %	53,40	48,24	1032	3301	23,13
60 %	45,77	41,04	1043	3354	23,55
50 %	38,14	34,13	1055	3396	23,87
40 %	30,52	27,14	1063	3425	24,07
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	***n* [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,82	7,33	46,15	1482	7,16	7,08
90 %	7,45	6,89	44,00	1482	6,83	6,72
80 %	7,13	6,83	42,00	1485	6,53	6,59
70 %	6,77	6,30	39,75	1485	6,18	6,15
60 %	6,43	6,02	37,60	1486	5,85	5,84
50 %	6,06	5,70	35,30	1486	5,49	5,49
40 %	5,67	5,42	33,00	1488	5,14	5,07
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from the throttling measurement 1.2. Maximum flow rate of 76,3 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m\eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	56,8 %	52,0 %	60,6 %	55,4 %	93,7 %	97,7 %	96,5 %	62,0 %	62,7 %	56,7 %	57,4 %
90 %	55,2 %	50,9 %	59,6 %	55,0 %	92,5 %	99,1 %	97,5 %	60,2 %	61,2 %	55,5 %	56,5 %
80 %	52,7 %	48,2 %	55,1 %	50,4 %	95,7 %	95,7 %	96,5 %	57,6 %	57,1 %	52,6 %	52,2 %
70 %	49,7 %	44,9 %	53,4 %	48,3 %	93,1 %	98,1 %	97,5 %	54,5 %	54,8 %	49,2 %	49,5 %
60 %	45,7 %	41,0 %	48,8 %	43,8 %	93,6 %	97,2 %	96,9 %	50,2 %	50,3 %	45,0 %	45,1 %
50 %	40,9 %	36,6 %	43,6 %	39,0 %	94,0 %	96,5 %	96,4 %	45,2 %	45,2 %	40,4 %	40,4 %
40 %	35,3 %	31,4 %	36,9 %	32,9 %	95,6 %	94,9 %	93,5 %	38,9 %	39,5 %	34,6 %	35,1 %
Error margin:	± 6 %	± 4,9 %	± 5,8 %	± 4,7 %	± 13,3 %	± 11,6 %	± 11,4 %	± 5,2 %	± 5,3 %	± 4,2 %	± 4,2 %



The total efficiencies of throttling measurement 1.2. Motor-pump efficiencies.

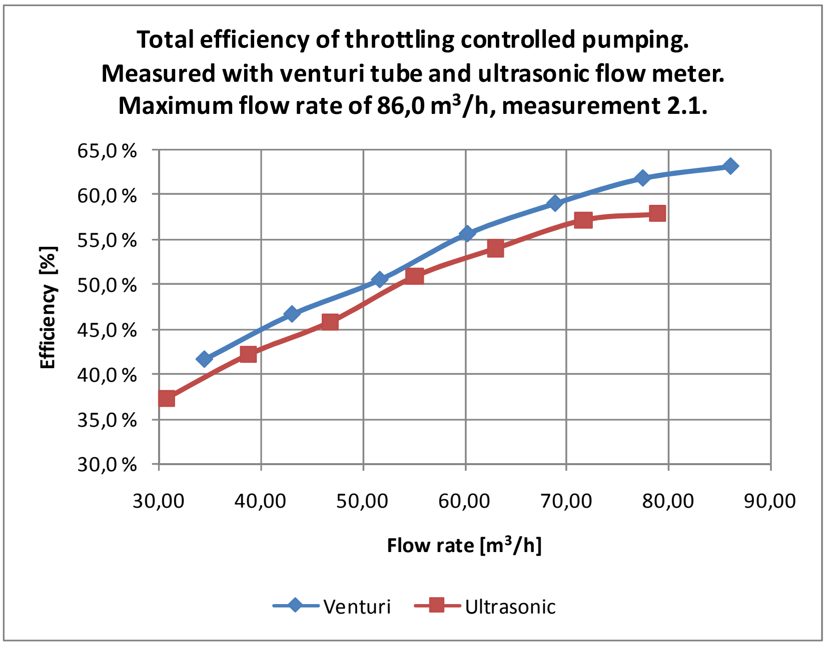
Results of throttling control measurement 2.1. Maximum flow rate of 86,0 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	**H [m]**
100 %	86,03	78,84	956	2954	20,37
90 %	77,43	71,64	977	3063	21,26
80 %	68,83	63,00	999	3160	22,03
70 %	60,22	55,08	1016	3238	22,66
60 %	51,62	46,80	1033	3310	23,21
50 %	43,02	38,88	1046	3367	23,66
40 %	34,41	30,85	1058	3410	23,98
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	8,30	7,56	48,85	1481	7,58	7,25
90 %	7,88	7,26	46,30	1482	7,19	7,15
80 %	7,46	7,00	43,75	1483	6,79	6,72
70 %	7,06	6,69	41,40	1484	6,43	6,43
60 %	6,67	6,47	39,00	1484	6,06	5,97
50 %	6,27	5,95	36,50	1485	5,68	5,60
40 %	5,86	5,41	34,00	1486	5,29	5,38
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from the throttling measurement 2.1. Maximum flow rate of 86,0 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	57,5 %	52,7 %	63,2 %	57,9 %	91,1 %	100,2 %	95,9 %	63,0 %	65,9 %	57,8 %	60,4 %
90 %	57,0 %	52,7 %	61,8 %	57,2 %	92,1 %	99,0 %	98,5 %	62,4 %	62,8 %	57,8 %	58,1 %
80 %	55,4 %	50,7 %	59,0 %	54,0 %	93,9 %	97,1 %	96,0 %	60,8 %	61,5 %	55,7 %	56,3 %
70 %	52,7 %	48,2 %	55,6 %	50,9 %	94,7 %	96,2 %	96,2 %	57,8 %	57,8 %	52,9 %	52,9 %
60 %	48,9 %	44,4 %	50,5 %	45,8 %	96,9 %	93,7 %	92,3 %	53,9 %	54,7 %	48,8 %	49,6 %
50 %	44,3 %	40,0 %	46,6 %	42,2 %	94,9 %	95,5 %	94,2 %	48,9 %	49,5 %	44,2 %	44,8 %
40 %	38,4 %	34,4 %	41,6 %	37,3 %	92,3 %	97,9 %	99,4 %	42,5 %	41,8 %	38,1 %	37,5 %
Error margin:	± 6,1 %	± 5 %	± 6,1 %	± 4,9 %	± 13,4 %	± 11,7 %	± 11,6 %	± 5,3 %	± 5,6 %	± 4,3 %	± 4,5 %



The total efficiencies of throttling measurement 2.1. Motor-pump efficiencies.

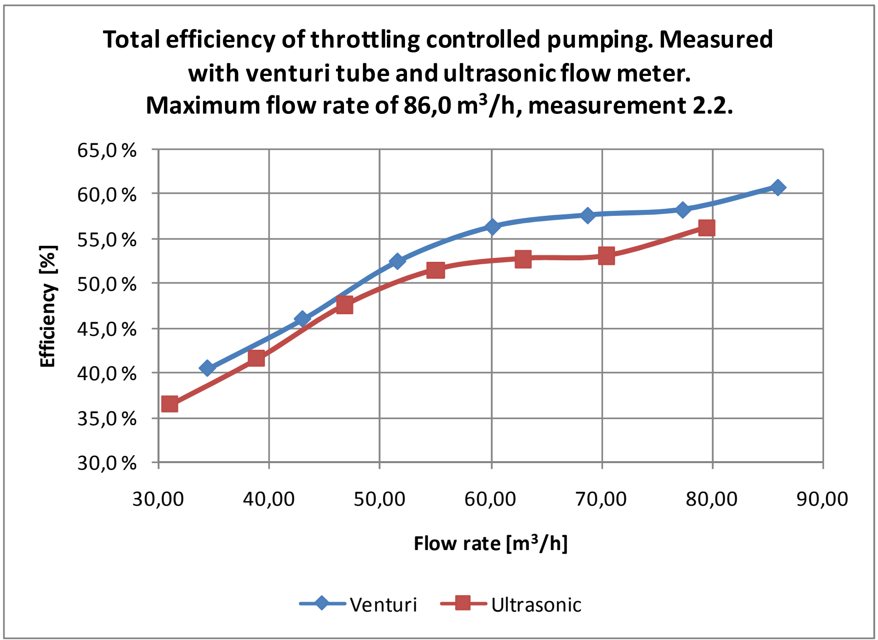
Results of throttling control measurement 2.2. Maximum flow rate of 86,0 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	**H [m]**
100 %	86,03	79,56	961	2954	20,32
90 %	77,43	70,56	982	3067	21,25
80 %	68,83	63,00	1003	3159	21,98
70 %	60,22	55,08	1020	3245	22,68
60 %	51,62	46,80	1037	3315	23,22
50 %	43,02	38,88	1049	3369	23,65
40 %	34,41	31,03	1060	3410	23,95
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	8,36	7,84	49,30	1482	7,65	7,49
90 %	7,88	7,70	46,65	1482	7,24	7,27
80 %	7,47	7,16	44,15	1483	6,86	6,95
70 %	7,08	6,61	41,60	1484	6,46	6,43
60 %	6,66	6,23	39,05	1485	6,07	6,14
50 %	6,28	6,03	36,75	1486	5,72	5,64
40 %	5,87	5,55	34,20	1486	5,32	5,42
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from the throttling measurement 2.1. Maximum flow rate of 86,0 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	57,0 %	52,7 %	60,8 %	56,2 %	93,8 %	97,6 %	95,5 %	62,3 %	63,6 %	57,6 %	58,8 %
90 %	56,9 %	51,9 %	58,2 %	53,1 %	97,7 %	94,0 %	94,4 %	61,9 %	61,7 %	56,4 %	56,3 %
80 %	55,2 %	50,5 %	57,6 %	52,7 %	95,8 %	95,8 %	97,1 %	60,1 %	59,4 %	55,0 %	54,3 %
70 %	52,6 %	48,1 %	56,3 %	51,5 %	93,4 %	97,9 %	97,3 %	57,6 %	57,9 %	52,6 %	53,0 %
60 %	49,0 %	44,5 %	52,5 %	47,6 %	93,5 %	97,6 %	98,6 %	53,8 %	53,2 %	48,8 %	48,2 %
50 %	44,1 %	39,9 %	46,0 %	41,6 %	95,9 %	94,9 %	93,6 %	48,5 %	49,1 %	43,8 %	44,4 %
40 %	38,3 %	34,5 %	40,5 %	36,5 %	94,5 %	95,9 %	97,7 %	42,2 %	41,4 %	38,1 %	37,4 %
Error margins:	± 6 %	± 5 %	± 5,8 %	± 4,8 %	± 13,5 %	± 11,5 %	± 11,5 %	± 5,3 %	± 5,4 %	± 4,2 %	± 4,3 %



The total efficiencies of throttling measurement 2.2. Motor-pump efficiencies.

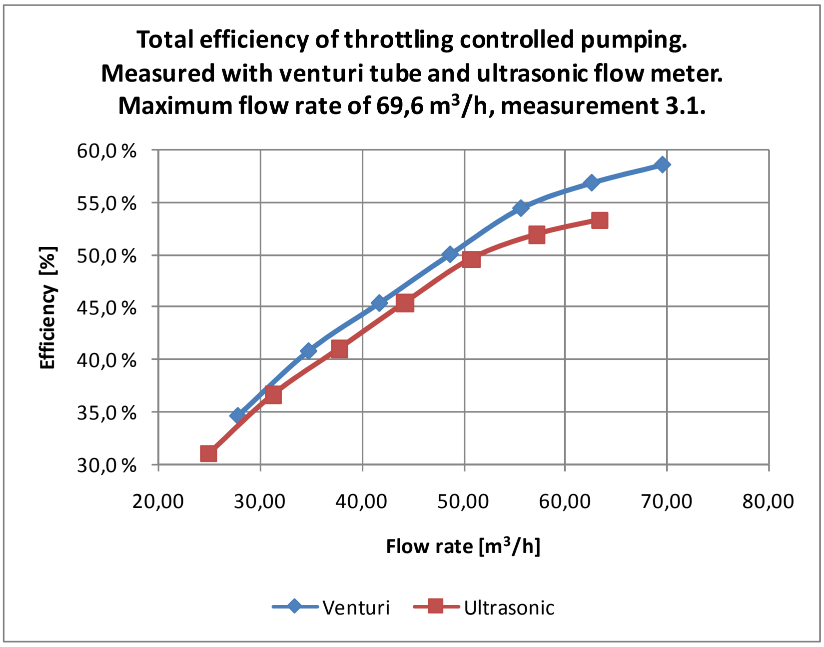
Results of throttling control measurement 3.1. Maximum flow rate of 69,6 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	69,60	63,36	998	3154	21,98
90 %	62,64	57,24	1014	3218	22,47
80 %	55,68	50,76	1028	3281	22,97
70 %	48,72	44,28	1040	3332	23,36
60 %	41,76	37,80	1051	3377	23,71
50 %	34,80	31,32	1060	3410	23,96
40 %	27,84	25,02	1067	3434	24,12
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	***n* [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,49	7,13	43,90	1482	6,81	6,93
90 %	7,18	6,76	42,05	1483	6,53	6,45
80 %	6,87	6,41	40,20	1484	6,25	6,22
70 %	6,55	6,21	38,20	1485	5,94	5,94
60 %	6,23	5,95	36,25	1486	5,64	5,63
50 %	5,87	5,57	34,20	1486	5,32	5,25
40 %	5,53	5,29	32,00	1488	4,99	5,00
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from the throttling measurement 3.1. Maximum flow rate of 69,6 m^3/h.

	Efficiencies											
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	55,7 %	50,7 %	58,5 %	53,3 %	95,1 %	95,6 %	97,2 %	61,2 %	60,2 %	55,7 %	54,8 %
90 %	53,5 %	48,9 %	56,8 %	51,9 %	94,1 %	96,7 %	95,5 %	58,7 %	59,5 %	53,7 %	54,3 %
80 %	50,8 %	46,3 %	54,4 %	49,6 %	93,4 %	97,5 %	97,0 %	55,8 %	56,0 %	50,9 %	51,1 %
70 %	47,4 %	43,1 %	50,0 %	45,4 %	94,8 %	95,7 %	95,7 %	52,2 %	52,2 %	47,5 %	47,5 %
60 %	43,3 %	39,2 %	45,3 %	41,0 %	95,5 %	94,8 %	94,6 %	47,8 %	47,9 %	43,3 %	43,4 %
50 %	38,7 %	34,8 %	40,8 %	36,7 %	94,9 %	95,5 %	94,3 %	42,7 %	43,3 %	38,4 %	38,9 %
40 %	33,1 %	29,7 %	34,6 %	31,1 %	95,6 %	94,3 %	94,6 %	36,7 %	36,6 %	33,0 %	32,9 %
Error margins:	± 5,9 %	± 4,8 %	± 5,6 %	± 4,5 %	± 13,3 %	± 11,4 %	± 11,4 %	± 5,2 %	± 5,1 %	± 4,1 %	± 4 %



The total efficiencies of throttling measurement 3.1. Motor-pump efficiencies.

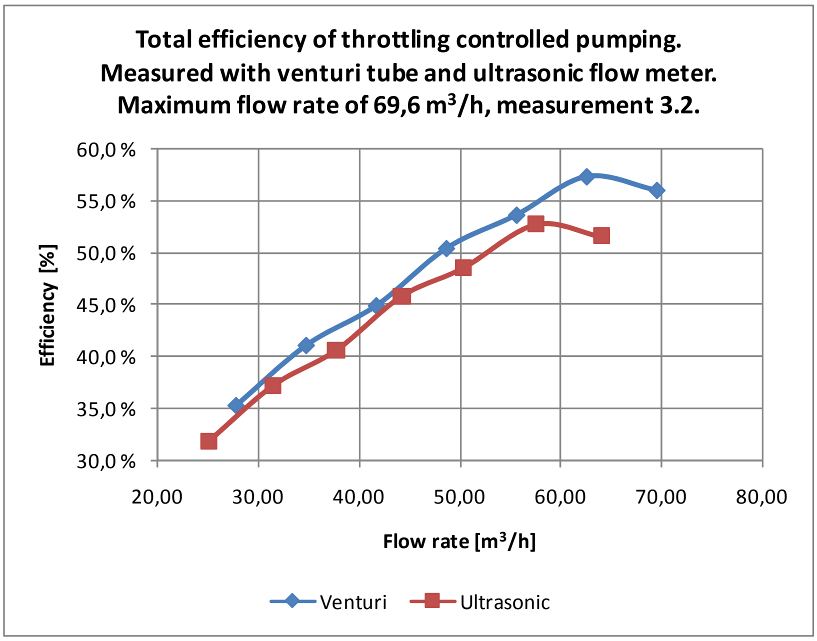
Results of throttling control measurement 3.2. Maximum flow rate of 69,6 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	69,60	64,08	1002	3155	21,95
90 %	62,64	57,60	1015	3222	22,49
80 %	55,68	50,40	1029	3287	23,01
70 %	48,72	44,28	1040	3334	23,38
60 %	41,76	37,80	1051	3376	23,70
50 %	34,80	31,57	1060	3408	23,93
40 %	27,84	25,20	1068	3434	24,12
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,5 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,53	7,44	43,90	1484	6,82	6,96
90 %	7,18	6,70	41,95	1484	6,52	6,49
80 %	6,86	6,52	39,90	1484	6,20	6,32
70 %	6,59	6,16	38,30	1485	5,96	5,97
60 %	6,22	6,01	36,20	1486	5,63	5,65
50 %	5,88	5,53	34,05	1486	5,30	5,36
40 %	5,55	5,19	32,00	1486	4,98	5,03
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from the throttling measurement 3.2. Maximum flow rate of 69,6 m^3/h.

	Efficiencies										
	Total efficiency		$\eta_m \eta_p$		η_d	η_m		η_p			
								Venturi		Ultrasonic	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	55,3 %	50,9 %	56,0 %	51,5 %	98,8 %	91,8 %	93,6 %	61,0 %	59,8 %	56,2 %	55,1 %
90 %	53,5 %	49,2 %	57,3 %	52,7 %	93,3 %	97,3 %	96,9 %	58,9 %	59,2 %	54,2 %	54,4 %
80 %	50,9 %	46,1 %	53,6 %	48,5 %	95,0 %	95,2 %	97,0 %	56,3 %	55,2 %	51,0 %	50,0 %
70 %	47,1 %	42,8 %	50,4 %	45,8 %	93,5 %	96,7 %	96,8 %	52,1 %	52,0 %	47,4 %	47,3 %
60 %	43,3 %	39,2 %	44,9 %	40,6 %	96,6 %	93,7 %	93,9 %	47,9 %	47,8 %	43,3 %	43,2 %
50 %	38,6 %	35,0 %	41,0 %	37,2 %	94,0 %	95,8 %	96,9 %	42,8 %	42,3 %	38,9 %	38,4 %
40 %	33,0 %	29,9 %	35,3 %	31,9 %	93,6 %	95,9 %	96,8 %	36,7 %	36,4 %	33,3 %	33,0 %
Error margin:	± 5,9 %	± 4,9 %	± 5,5 %	± 4,5 %	± 13,6 %	± 11,4 %	± 11,4 %	± 5,2 %	± 5 %	± 4,1 %	± 4,1 %



The total efficiencies of throttling measurement 3.2. Motor-pump efficiencies.

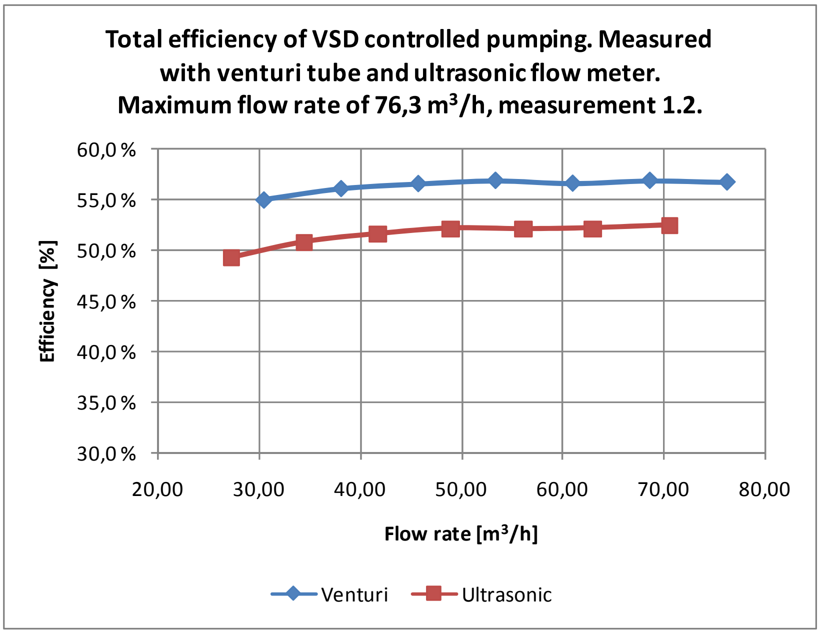
Results of VSD controlled pumping, measurement 1.2. Maximum flow rate of 76,3 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	76,29	70,56	987	3079	21,33
90 %	68,66	63,00	1004	2749	17,79
80 %	61,03	56,16	1020	2465	14,73
70 %	53,40	48,96	1034	2203	11,92
60 %	45,77	41,76	1047	1992	9,63
50 %	38,14	34,56	1058	1811	7,68
40 %	30,52	27,36	1066	1659	6,04
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	***n* [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,82	7,47	46,15	1481	7,16	6,97
90 %	5,86	5,35	38,20	1340	5,36	5,15
80 %	4,33	4,00	31,35	1205	3,96	3,81
70 %	3,05	2,69	24,95	1065	2,78	2,56
60 %	2,13	1,82	19,75	935	1,93	1,73
50 %	1,43	1,20	15,35	810	1,30	1,12
40 %	0,92	0,72	11,65	685	0,84	0,65
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from VSD controlled pumping, measurement 1.2. Maximum flow rate of 76,3 m^3/h.

	Efficiencies										
	Total efficiency		$\eta_m \eta_p$		η_d	η_m		η_p			
								Venturi		Ultrasonic	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	56,7 %	52,4 %	59,4 %	54,9 %	95,5 %	95,8 %	93,2 %	62,0 %	63,7 %	57,3 %	58,9 %
90 %	56,9 %	52,2 %	62,3 %	57,1 %	91,3 %	100,3 %	96,3 %	62,1 %	64,7 %	57,0 %	59,4 %
80 %	56,6 %	52,1 %	61,3 %	56,4 %	92,4 %	98,9 %	95,3 %	61,9 %	64,3 %	57,0 %	59,2 %
70 %	56,9 %	52,1 %	64,5 %	59,1 %	88,2 %	103,4 %	95,0 %	62,3 %	67,9 %	57,1 %	62,2 %
60 %	56,5 %	51,6 %	66,0 %	60,2 %	85,6 %	106,3 %	94,8 %	62,1 %	69,6 %	56,7 %	63,5 %
50 %	56,0 %	50,8 %	66,6 %	60,3 %	84,2 %	108,5 %	93,3 %	61,3 %	71,3 %	55,6 %	64,6 %
40 %	54,9 %	49,2 %	70,3 %	63,0 %	78,1 %	116,9 %	90,9 %	60,1 %	77,3 %	53,9 %	69,3 %
Error margins:	± 7,1 %	± 5,8 %	± 6,7 %	± 5,4 %	± 13,2 %	± 13,7 %	± 11,3 %	± 5,3 %	± 6,5 %	± 4,2 %	± 5,1 %



Efficiencies calculated from VSD controlled pumping, measurement 1.2.

Appendix D: VSD controlled pumping results. Page 2

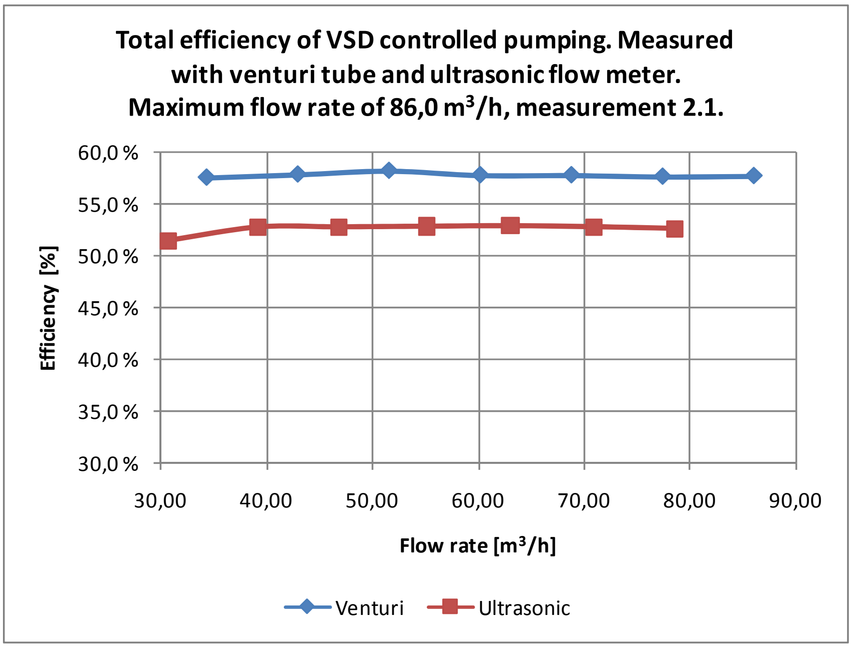
Results of VSD controlled pumping, measurement 2.1. Maximum flow rate of 86,0 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	**H [m]**
100 %	86,03	78,48	947	2951	20,43
90 %	77,43	70,92	969	2655	17,18
80 %	68,83	63,00	990	2391	14,28
70 %	60,22	55,08	1008	2155	11,69
60 %	51,62	46,80	1024	1946	9,39
50 %	43,02	39,24	1037	1780	7,58
40 %	34,41	30,78	1048	1635	5,98
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	8,30	7,53	49,20	1481	7,63	7,19
90 %	6,29	5,93	41,15	1345	5,80	5,67
80 %	4,64	4,33	33,80	1210	4,28	4,12
70 %	3,32	3,04	27,20	1075	3,06	2,89
60 %	2,27	1,95	21,40	940	2,11	1,84
50 %	1,54	1,32	16,75	815	1,43	1,24
40 %	0,98	0,74	12,75	690	0,92	0,68
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from VSD controlled pumping, measurement 2.1. Maximum flow rate of 86,0 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	57,7 %	52,6 %	63,6 %	58,1 %	90,7 %	101,4 %	95,5 %	62,8 %	66,6 %	57,3 %	60,8 %
90 %	57,6 %	52,8 %	61,1 %	56,0 %	94,3 %	97,7 %	95,5 %	62,6 %	64,0 %	57,3 %	58,6 %
80 %	57,8 %	52,9 %	61,9 %	56,7 %	93,3 %	99,0 %	95,1 %	62,5 %	65,1 %	57,2 %	59,6 %
70 %	57,8 %	52,8 %	63,1 %	57,7 %	91,6 %	100,7 %	94,9 %	62,6 %	66,5 %	57,3 %	60,8 %
60 %	58,2 %	52,8 %	67,8 %	61,4 %	85,9 %	108,0 %	94,1 %	62,7 %	72,0 %	56,9 %	65,3 %
50 %	57,9 %	52,8 %	67,3 %	61,4 %	86,0 %	108,3 %	93,6 %	62,1 %	71,9 %	56,7 %	65,6 %
40 %	57,5 %	51,5 %	75,8 %	67,8 %	75,9 %	124,5 %	91,9 %	60,9 %	82,5 %	54,5 %	73,8 %
Error margins:	± 7,4 %	± 6 %	± 7,3 %	± 5,8 %	± 13,1 %	± 14,6 %	± 11,2 %	± 5,3 %	± 7 %	± 4,2 %	± 5,4 %



Efficiencies calculated from VSD controlled pumping, measurement 2.1.

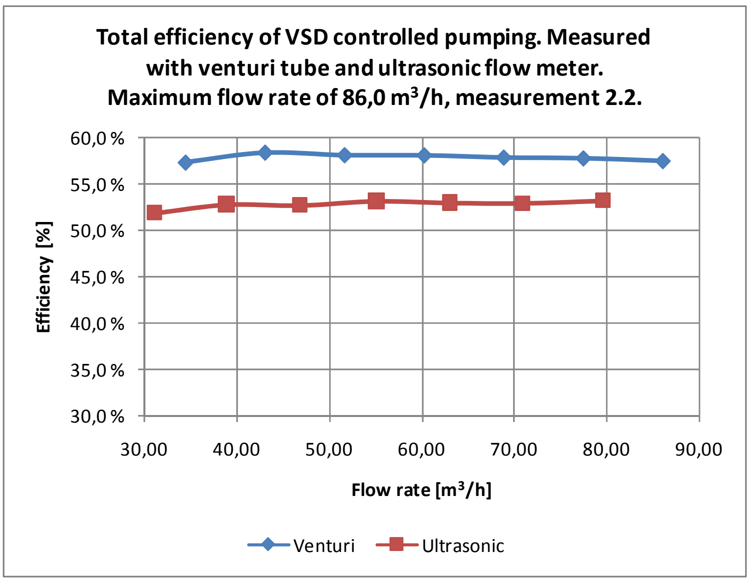
Results of VSD controlled pumping, measurement 2.2. Maximum flow rate of 86,0 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	86,03	79,56	946	2946	20,39
90 %	77,43	70,92	968	2649	17,13
80 %	68,83	63,00	989	2380	14,18
70 %	60,22	55,08	1008	2159	11,73
60 %	51,62	46,80	1024	1957	9,52
50 %	43,02	38,88	1037	1782	7,59
40 %	34,41	31,14	1048	1642	6,05
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	8,32	7,88	49,30	1482	7,65	7,53
90 %	6,26	5,84	41,10	1345	5,79	5,57
80 %	4,60	4,22	33,60	1205	4,24	4,02
70 %	3,32	3,00	27,10	1075	3,05	2,88
60 %	2,31	1,97	21,50	945	2,13	1,86
50 %	1,53	1,33	16,65	815	1,42	1,25
40 %	0,99	0,79	12,75	695	0,93	0,73
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from VSD controlled pumping, measurement 2.2. Maximum flow rate of 86,0 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	57,5 %	53,1 %	60,7 %	56,1 %	94,7 %	97,1 %	95,5 %	62,5 %	63,5 %	57,8 %	58,8 %
90 %	57,7 %	52,9 %	61,9 %	56,7 %	93,2 %	99,2 %	95,5 %	62,4 %	64,9 %	57,2 %	59,4 %
80 %	57,8 %	52,9 %	63,0 %	57,7 %	91,7 %	100,5 %	95,1 %	62,7 %	66,2 %	57,4 %	60,6 %
70 %	58,1 %	53,1 %	64,2 %	58,7 %	90,5 %	101,7 %	96,0 %	63,1 %	66,8 %	57,7 %	61,1 %
60 %	58,1 %	52,7 %	68,0 %	61,6 %	85,5 %	108,0 %	94,2 %	62,9 %	72,2 %	57,0 %	65,4 %
50 %	58,3 %	52,7 %	66,9 %	60,5 %	87,2 %	106,8 %	93,6 %	62,6 %	71,5 %	56,6 %	64,6 %
40 %	57,3 %	51,8 %	72,3 %	65,4 %	79,3 %	118,2 %	93,0 %	61,1 %	77,7 %	55,3 %	70,3 %
Error margins:	± 7,3 %	± 6 %	± 6,9 %	± 5,6 %	± 13,2 %	± 13,8 %	± 11,2 %	± 5,3 %	± 6,6 %	± 4,3 %	± 5,2 %



Efficiencies calculated from VSD controlled pumping, measurement 2.2.

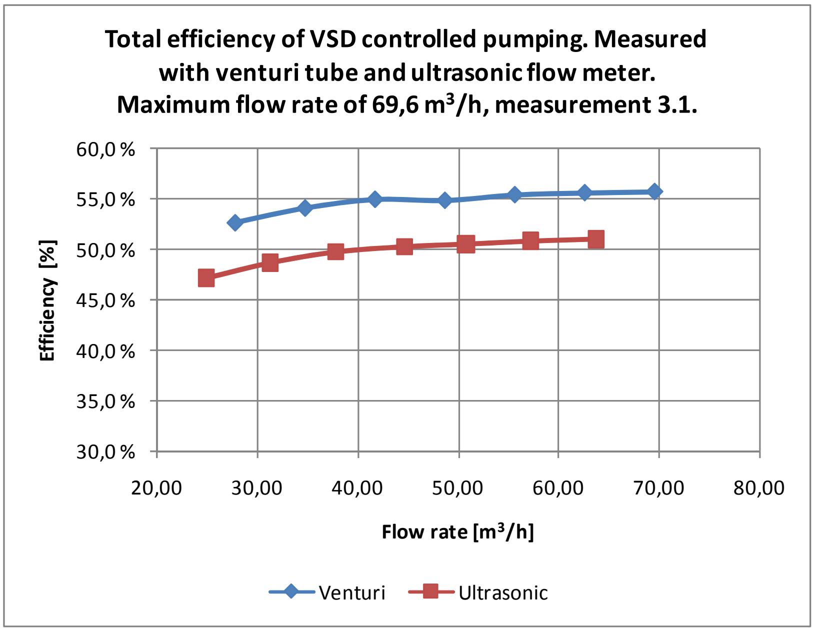
Results of VSD controlled pumping, measurement 3.1. Maximum flow rate of 69,6 m^3/h.

Flow rate			Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	69,60	63,72	988	3141	21,95
90 %	62,64	57,24	1002	2806	18,39
80 %	55,68	50,76	1016	2498	15,11
70 %	48,72	44,64	1028	2244	12,40
60 %	41,76	37,80	1038	2011	9,91
50 %	34,80	31,32	1048	1817	7,84
40 %	27,84	24,95	1055	1663	6,20
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	***n* [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,48	7,06	44,35	1482	6,88	6,75
90 %	5,65	5,13	37,00	1345	5,21	4,91
80 %	4,14	3,83	30,30	1205	3,82	3,65
70 %	3,01	2,70	24,70	1075	2,78	2,56
60 %	2,06	1,80	19,40	940	1,91	1,70
50 %	1,38	1,15	15,10	810	1,28	1,08
40 %	0,90	0,69	11,65	690	0,84	0,65
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from VSD controlled pumping, measurement 3.1. Maximum flow rate of 69,6 m^3/h.

	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	55,7 %	51,0 %	59,0 %	54,0 %	94,3 %	97,6 %	95,7 %	60,5 %	61,7 %	55,4 %	56,5 %
90 %	55,6 %	50,8 %	61,2 %	55,9 %	90,8 %	101,6 %	95,6 %	60,2 %	64,0 %	55,0 %	58,5 %
80 %	55,4 %	50,5 %	59,9 %	54,6 %	92,4 %	100,0 %	95,3 %	59,9 %	62,9 %	54,6 %	57,3 %
70 %	54,8 %	50,2 %	61,0 %	55,9 %	89,9 %	103,0 %	94,8 %	59,2 %	64,3 %	54,3 %	58,9 %
60 %	54,9 %	49,7 %	62,9 %	56,9 %	87,3 %	106,4 %	94,7 %	59,1 %	66,4 %	53,5 %	60,1 %
50 %	54,0 %	48,6 %	64,9 %	58,4 %	83,3 %	111,9 %	93,9 %	58,0 %	69,1 %	52,2 %	62,2 %
40 %	52,6 %	47,1 %	68,2 %	61,1 %	77,1 %	122,0 %	93,5 %	55,9 %	73,0 %	50,1 %	65,4 %
Error margins:	± 6,8 %	± 5,6 %	± 6,5 %	± 5,2 %	± 13 %	± 14,3 %	± 11,2 %	± 5,1 %	± 6,2 %	± 4,1 %	± 4,8 %



Efficiencies calculated from VSD controlled pumping, measurement 3.1.

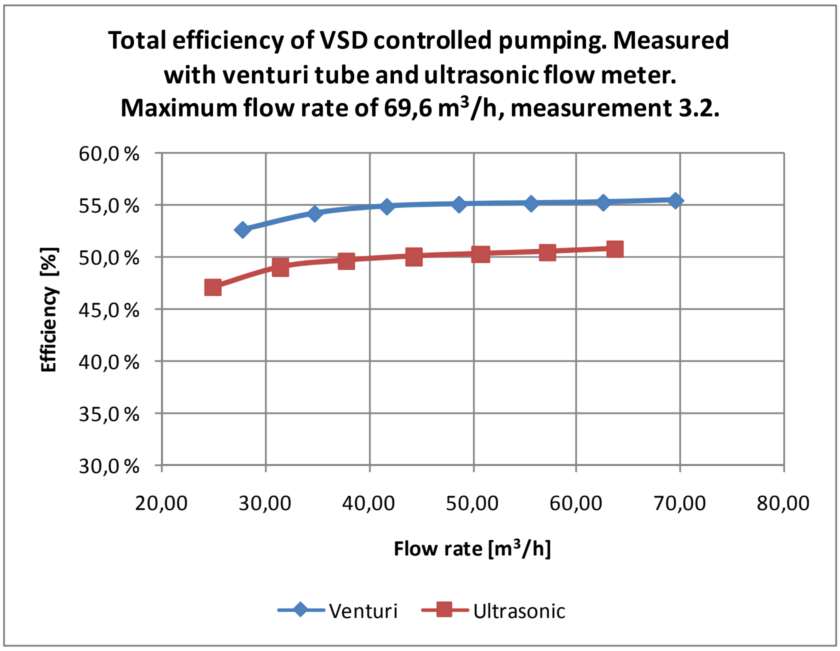
Results of VSD controlled pumping, measurement 3.2. Maximum flow rate of 69,6 m^3/h.

	Flow rate		Pressure		Total head
Flow rate	**Venturi [m^3/h]**	**Ultrasonic [m^3/h]**	**Inlet [mbar]**	**Outlet [mbar]**	***H* [m]**
100 %	69,60	63,72	987	3144	21,98
90 %	62,64	57,24	1000	2802	18,37
80 %	55,68	50,76	1011	2493	15,10
70 %	48,72	44,28	1023	2231	12,32
60 %	41,76	37,80	1033	2007	9,93
50 %	34,80	31,50	1043	1813	7,85
40 %	27,84	24,95	1049	1658	6,21
Error margins:	± 2 %	± 1 %	± 0,6 %	± 0,7 %	± 1 %

	Power					
Flow rate	**Input [kW]**	**$P_{m,in}$ [kW]**	**Torque [Nm]**	**n [1/min]**	**$P_{m,out}$ [kW]**	**$P_{m,actual}$ [kW]**
100 %	7,52	7,10	44,85	1484	6,97	6,80
90 %	5,68	5,31	37,40	1345	5,27	5,07
80 %	4,16	3,79	30,40	1205	3,84	3,61
70 %	2,97	2,68	24,45	1070	2,74	2,53
60 %	2,06	1,79	19,50	940	1,92	1,69
50 %	1,38	1,13	15,15	810	1,29	1,06
40 %	0,90	0,71	11,65	690	0,84	0,66
Error margins:	± (6,6 % + 20 W)	± 6 %	± 4 %	± 1 %	± 5 %	± 5 %

Efficiencies calculated from VSD controlled pumping, measurement 3.2. Maximum flow rate of 69,6 m^3/h.

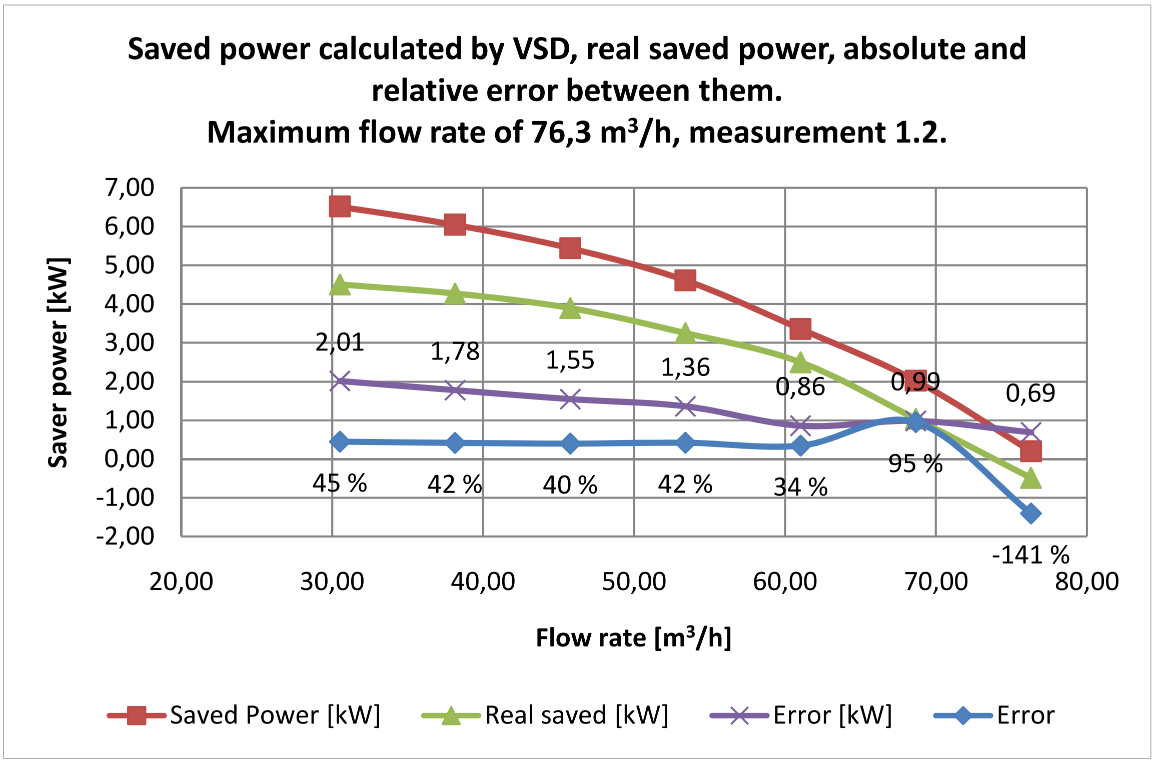
	Efficiencies										
	Total efficiency		**$\eta_m \eta_p$**		**η_d**	**η_m**		**η_p**			
								Venturi		**Ultrasonic**	
Flow rate	**Venturi**	**Ultrasonic**	**Venturi**	**Ultrasonic**		**Torque tr.**	**VSD**	**Torque tr.**	**VSD**	**Torque tr.**	**VSD**
100 %	55,4 %	50,8 %	58,7 %	53,8 %	94,4 %	98,2 %	95,7 %	59,8 %	61,4 %	54,8 %	56,2 %
90 %	55,2 %	50,5 %	59,0 %	54,0 %	93,6 %	99,2 %	95,5 %	59,5 %	61,8 %	54,4 %	56,5 %
80 %	55,1 %	50,3 %	60,5 %	55,1 %	91,2 %	101,2 %	95,3 %	59,7 %	63,5 %	54,5 %	57,9 %
70 %	55,1 %	50,0 %	61,0 %	55,5 %	90,2 %	102,2 %	94,2 %	59,7 %	64,8 %	54,3 %	58,9 %
60 %	54,9 %	49,7 %	63,3 %	57,3 %	86,7 %	107,5 %	94,4 %	58,9 %	67,1 %	53,3 %	60,7 %
50 %	54,2 %	49,0 %	65,9 %	59,7 %	82,2 %	113,7 %	93,8 %	58,0 %	70,3 %	52,5 %	63,6 %
40 %	52,6 %	47,1 %	66,8 %	59,8 %	78,8 %	119,4 %	92,9 %	55,9 %	71,9 %	50,1 %	64,4 %
Error margins:	± 6,8 %	± 5,6 %	± 6,4 %	± 5,1 %	± 13 %	± 14 %	± 11,2 %	± 5,1 %	± 6,1 %	± 4 %	± 4,8 %



Efficiencies calculated from VSD controlled pumping, measurement 3.2.

Saved power, real saved power and relative error between them. Maximum flow rate of 76,3 m^3/h. Measurement 1.2. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the -141 % error could be anything between -215 % and -67 %.

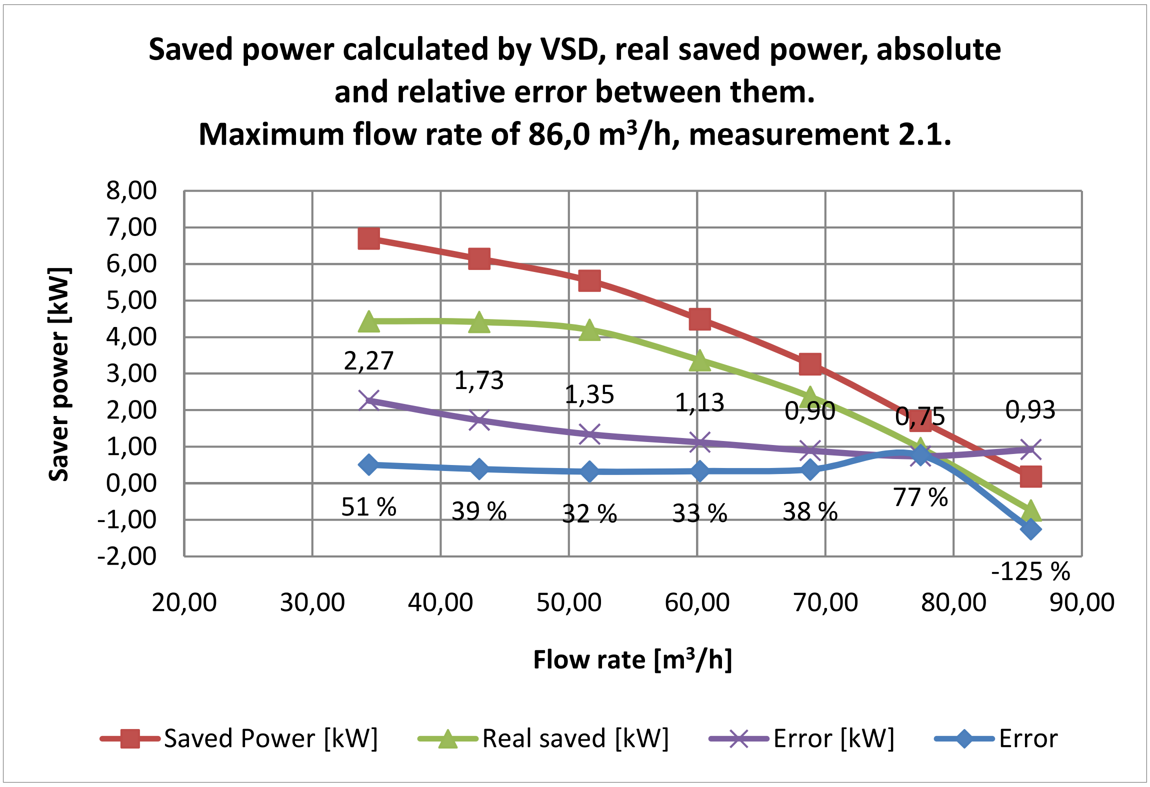
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	76,29	0,20	-0,49	-141 %	± 74 %
90 %	68,66	2,02	1,04	95 %	± 29 %
80 %	61,03	3,36	2,50	34 %	± 9,0 %
70 %	53,40	4,61	3,25	42 %	± 7,2 %
60 %	45,77	5,44	3,90	40 %	± 5,9 %
50 %	38,14	6,05	4,27	42 %	± 5,5 %
40 %	30,52	6,52	4,51	45 %	± 5,3 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗



Saved power, real saved power, absolute and the relative error between them. Measurement 1.2 at maximum flow rate of 76,3 m^3/h.

Saved power, real saved power and relative error between them. Maximum flow rate of 86,0 m^3/h. Measurement 2.1. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 77 % error could be anything between 48 % and 106 %.

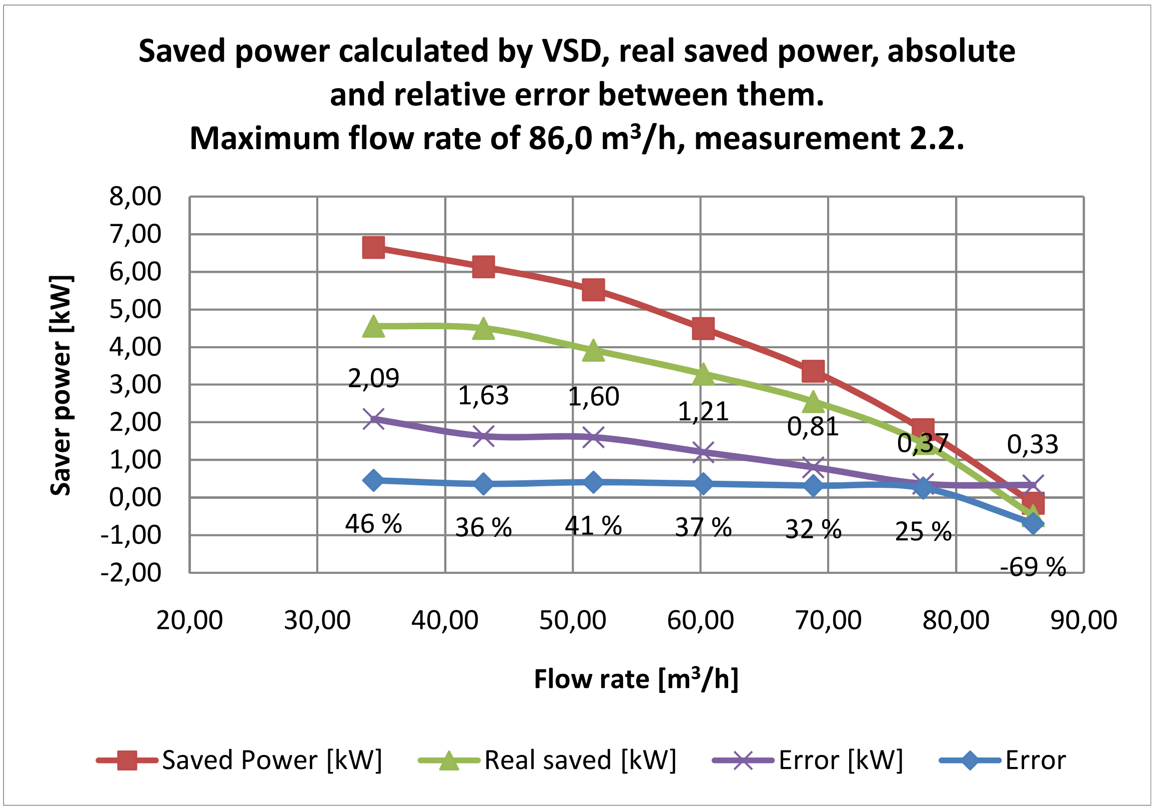
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	86,03	0,19	-0,74	-125 %	± 46 %
90 %	77,43	1,71	0,97	77 %	± 29 %
80 %	68,83	3,26	2,37	38 %	± 10 %
70 %	60,22	4,49	3,37	33 %	± 6,6 %
60 %	51,62	5,54	4,20	32 %	± 5,3 %
50 %	43,02	6,14	4,41	39 %	± 5,2 %
40 %	34,41	6,70	4,43	51 %	± 5,6 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗



Saved power, real saved power, absolute and the relative error between them. Measurement 2.1 at maximum flow rate of 86,0 m^3/h.

Saved power, real saved power and relative error between them. Maximum flow rate of 86,0 m^3/h. Measurement 2.2. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 25 % error could be anything between 10 % and 40 %.

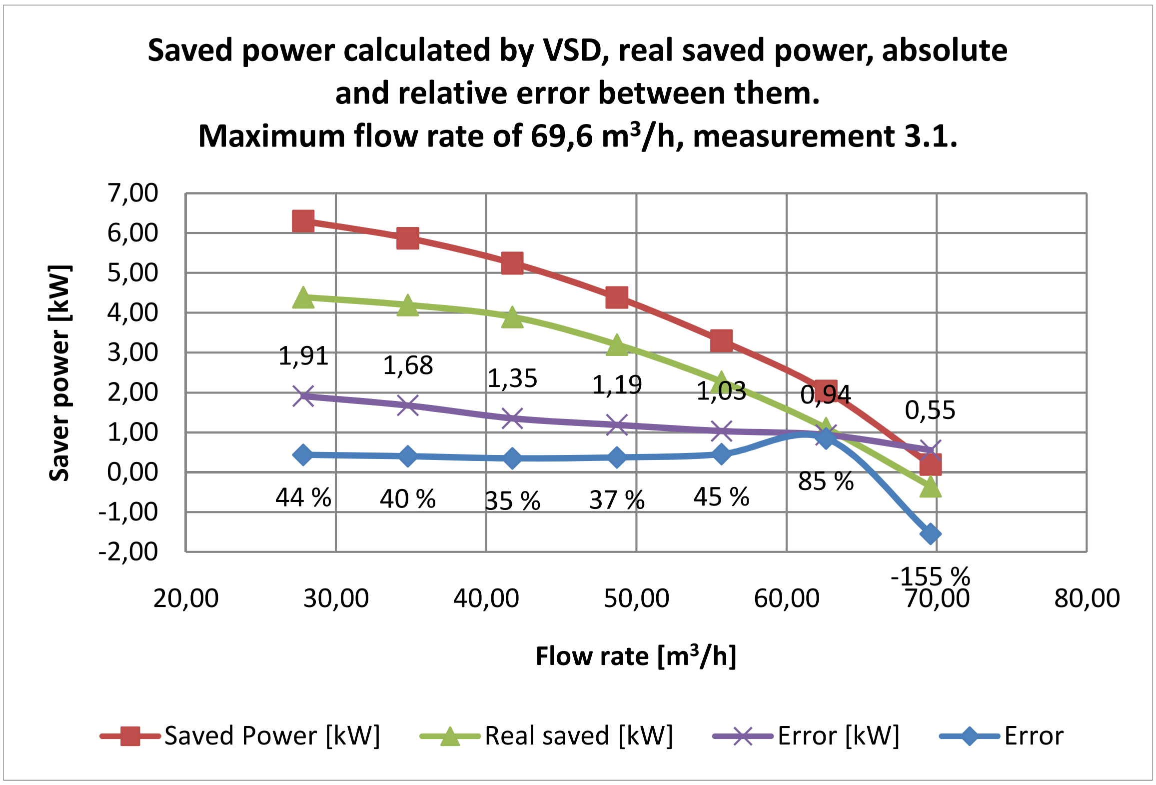
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	86,03	-0,15	-0,48	-69 %	± 56 %
90 %	77,43	1,81	1,44	25 %	± 15 %
80 %	68,83	3,36	2,56	32 %	± 8,6 %
70 %	60,22	4,50	3,29	37 %	± 6,9 %
60 %	51,62	5,52	3,92	41 %	± 5,9 %
50 %	43,02	6,13	4,50	36 %	± 5,0 %
40 %	34,41	6,65	4,56	46 %	± 5,3 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗



Saved power, real saved power, absolute and the relative error between them. Measurement 2.2 at maximum flow rate of 86,0 m^3/h.

Saved power, real saved power and relative error between them. Maximum flow rate of 69,6 m^3/h. Measurement 3.1. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 85 % error could be anything between 59 % and 111 %.

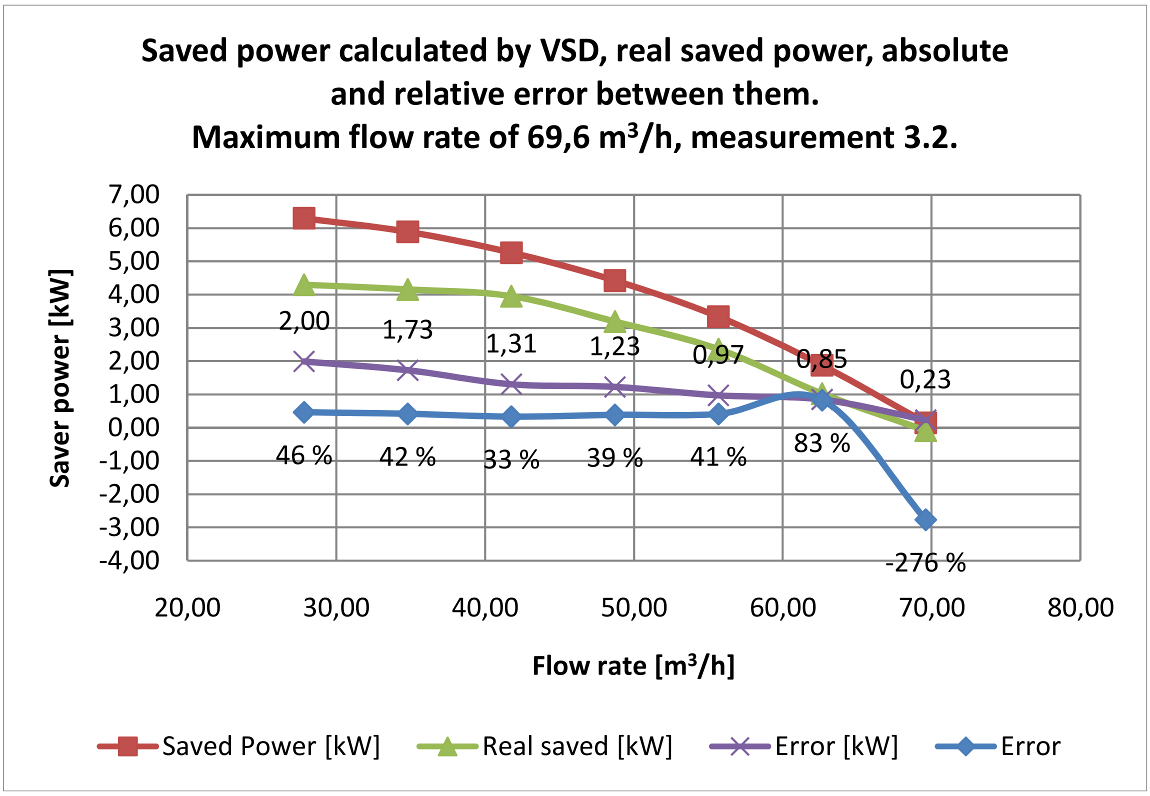
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	69,60	0,20	-0,36	-155 %	± 107 %
90 %	62,64	2,04	1,11	85 %	± 26 %
80 %	55,68	3,30	2,27	45 %	± 11 %
70 %	48,72	4,39	3,20	37 %	± 7,1 %
60 %	41,76	5,25	3,90	35 %	± 5,8 %
50 %	34,80	5,87	4,20	40 %	± 5,5 %
40 %	27,84	6,30	4,39	44 %	± 5,4 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗



Saved power, real saved power, absolute and the relative error between them. Measurement 3.1 at maximum flow rate of 69,6 m^3/h.

Saved power, real saved power and relative error between them. Maximum flow rate of 69,6 m^3/h. Measurement 3.2. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 41 % error could be anything between 31 % and 51 %.

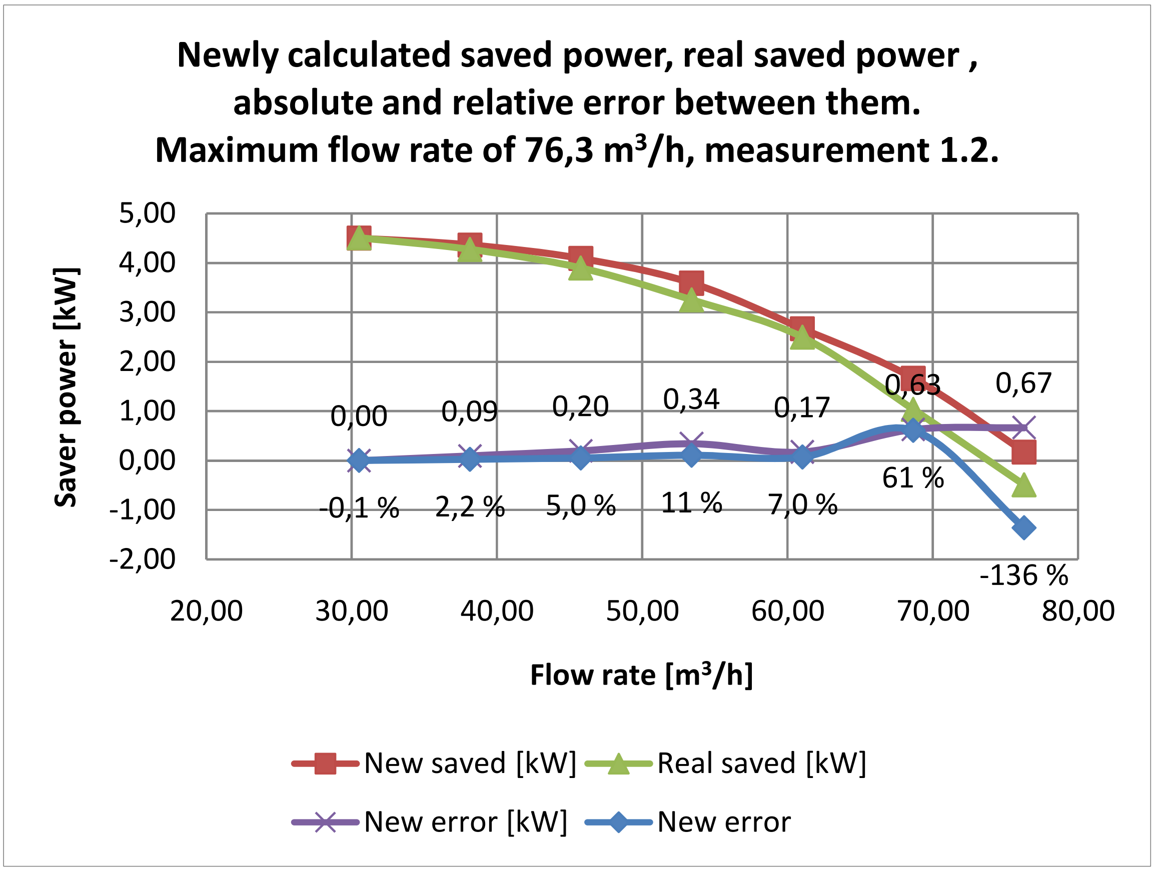
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	Saved Power [kW]	Real saved [kW]	Error	Error margins:
100 %	69,60	0,15	-0,08	-276 %	± 635 %
90 %	62,64	1,88	1,03	83 %	± 28 %
80 %	55,68	3,34	2,36	41 %	± 10 %
70 %	48,72	4,42	3,19	39 %	± 7,2 %
60 %	41,76	5,26	3,95	33 %	± 5,6 %
50 %	34,80	5,89	4,16	42 %	± 5,6 %
40 %	27,84	6,29	4,30	46 %	± 5,6 %
Error margins:	± 2 %	± 5 %	± 13 %	⇨	⇗



Saved power, real saved power, absolute and the relative error between them. Measurement 3.2 at maximum flow rate of 69,6 m^3/h.

Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 76,3 m^3/h, measurement 1.2. The error margins in the table below are percentages of the measured values except for the error margins of new error which are absolute values meaning that for example the 7,0 % error could be anything between -0,6 % and 14,6 %.

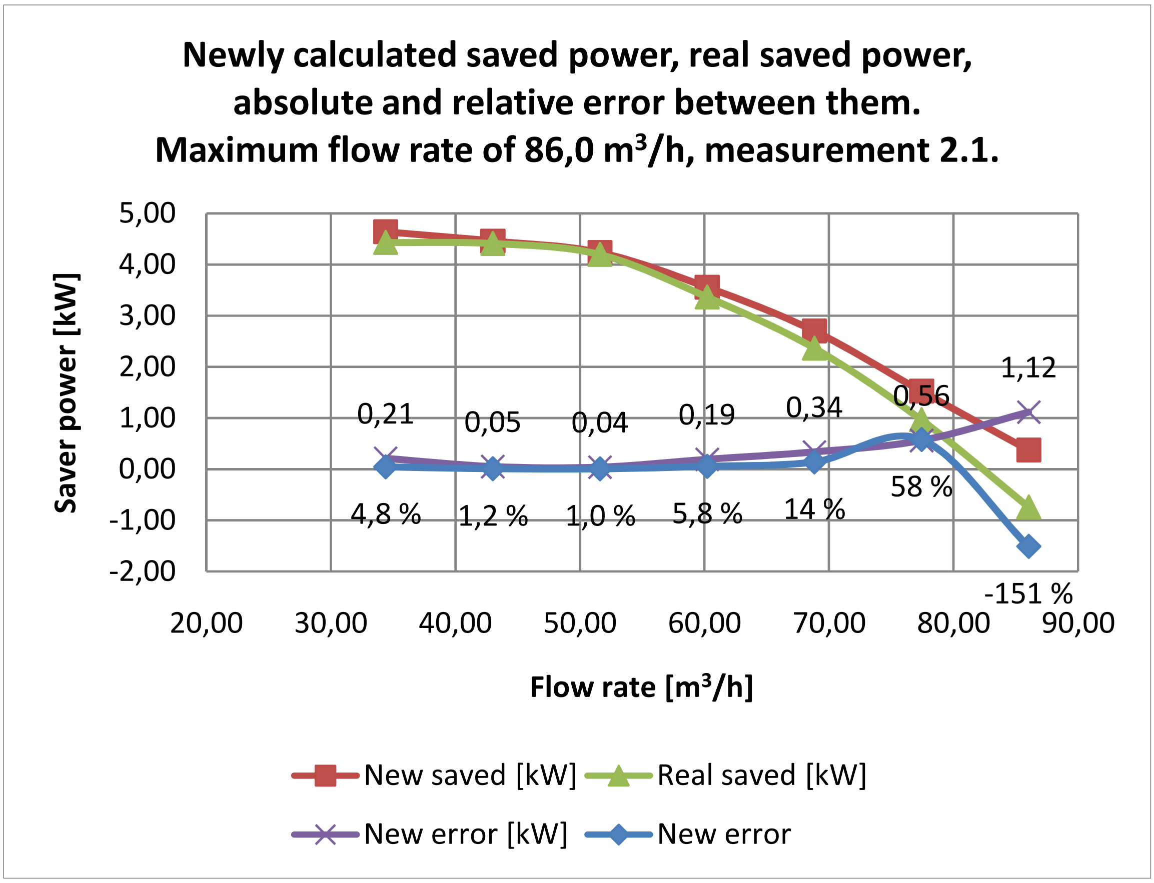
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	76,29	0,18	-0,49	-136 %	± 73 %
90 %	68,66	1,67	1,04	61 %	± 25 %
80 %	61,03	2,67	2,50	7,0 %	± 7,6 %
70 %	53,40	3,59	3,25	11 %	± 6,0 %
60 %	45,77	4,09	3,90	5,0 %	± 4,8 %
50 %	38,14	4,36	4,27	2,2 %	± 4,3 %
40 %	30,52	4,50	4,51	-0,1 %	± 4,0 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗



Newly calculated saved power, real saved power, absolute and relative error between them. Maximum flow rate of 76,3 m^3/h, measurement 1.2.

Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 86,0 m^3/h, measurement 2.1. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 5,8 % error could be anything between 0,2 % and 11,4 %.

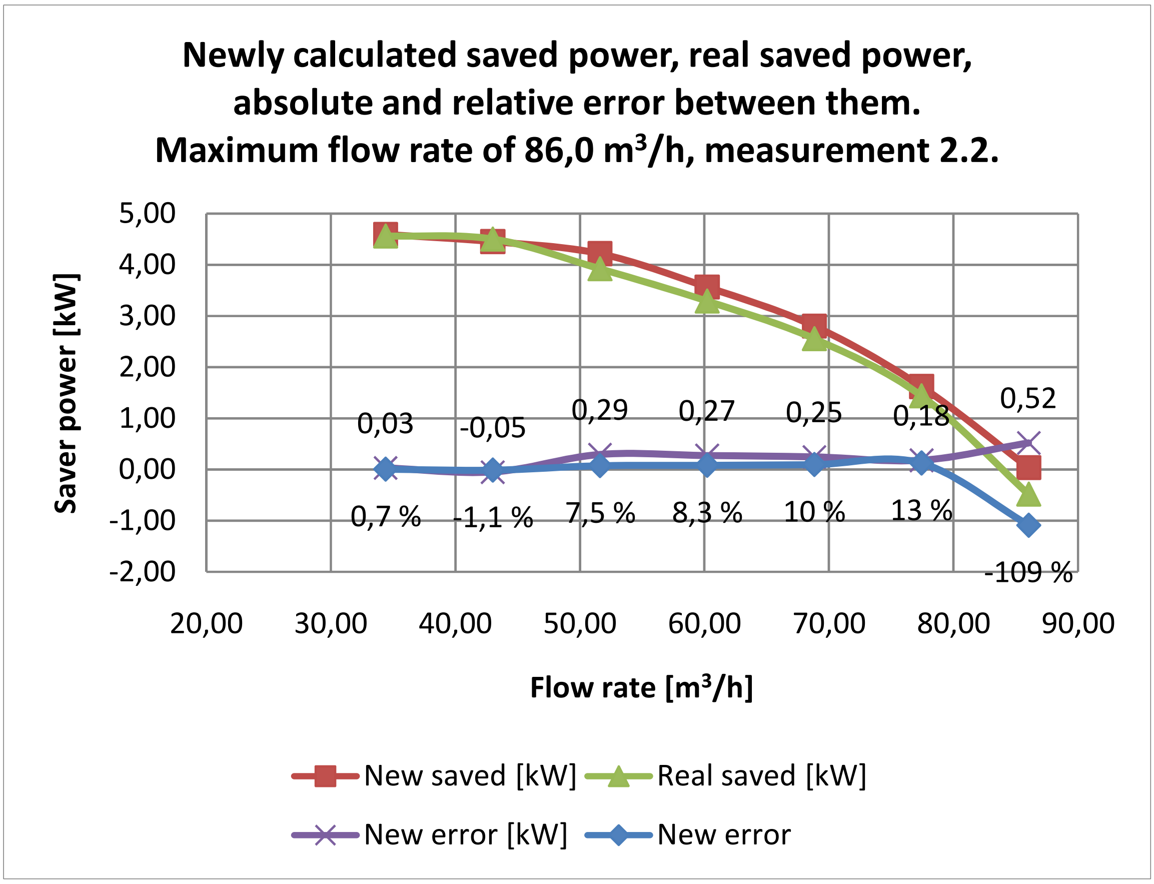
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	86,03	0,38	-0,74	-151 %	± 51 %
90 %	77,43	1,53	0,97	58 %	± 27 %
80 %	68,83	2,70	2,37	14 %	± 8,4 %
70 %	60,22	3,56	3,37	5,8 %	± 5,6 %
60 %	51,62	4,23	4,20	1,0 %	± 4,3 %
50 %	43,02	4,46	4,41	1,2 %	± 4,1 %
40 %	34,41	4,64	4,43	4,8 %	± 4,2 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗



Newly calculated saved power, real saved power, absolute and relative error between them. Maximum flow rate of 86,0 m^3/h, measurement 2.1.

Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 86,0 m^3/h, measurement 2.2. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the 10 % error could be anything between 2,4 % and 17,6 %.

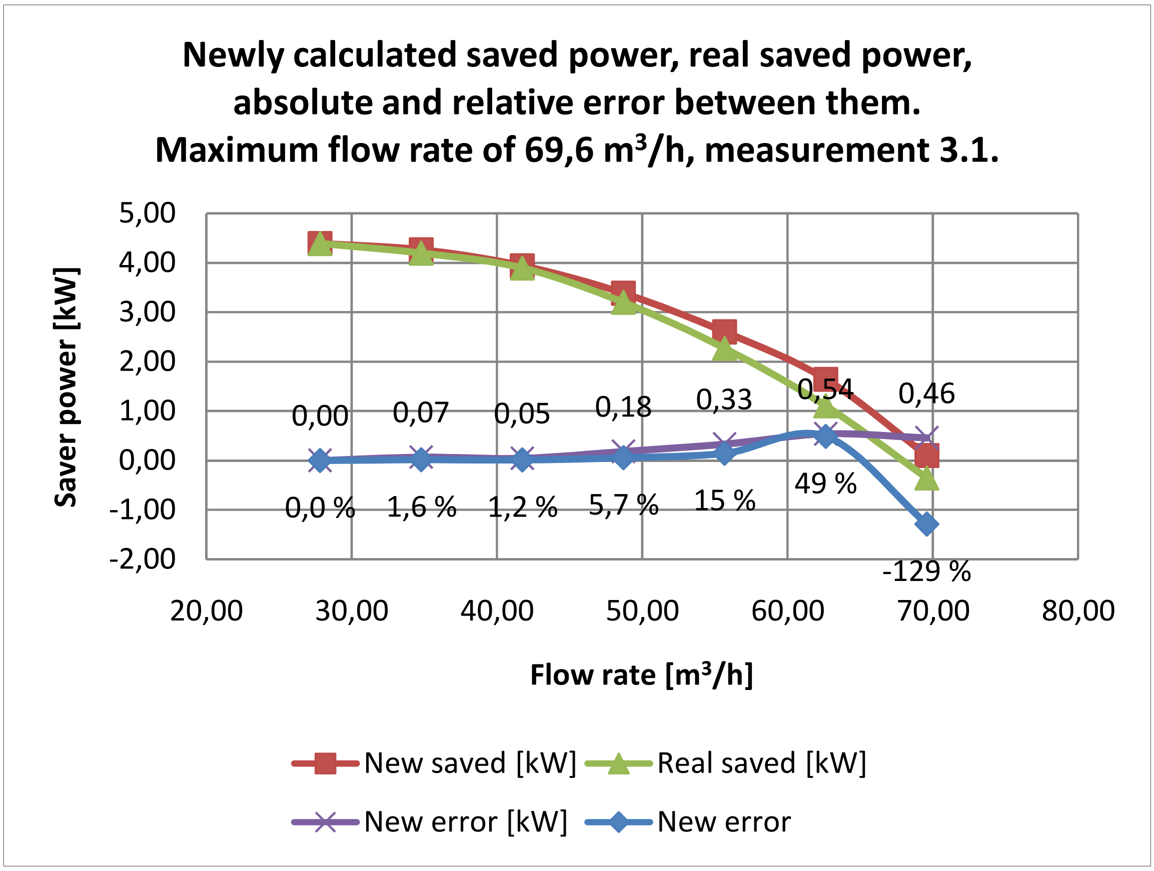
Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	86,03	0,04	-0,48	-109 %	± 67 %
90 %	77,43	1,62	1,44	13 %	± 14 %
80 %	68,83	2,80	2,56	10 %	± 7,6 %
70 %	60,22	3,56	3,29	8,3 %	± 5,8 %
60 %	51,62	4,21	3,92	7,5 %	± 4,9 %
50 %	43,02	4,45	4,50	-1,1 %	± 4,1 %
40 %	34,41	4,59	4,56	0,7 %	± 4,0 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗



Newly calculated saved power, real saved power, absolute and relative error between them. Maximum flow rate of 86,0 m^3/h, measurement 2.2.

Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 69,6 m^3/h, measurement 3.1. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the -129 % error could be anything between -227 % and -31 %.

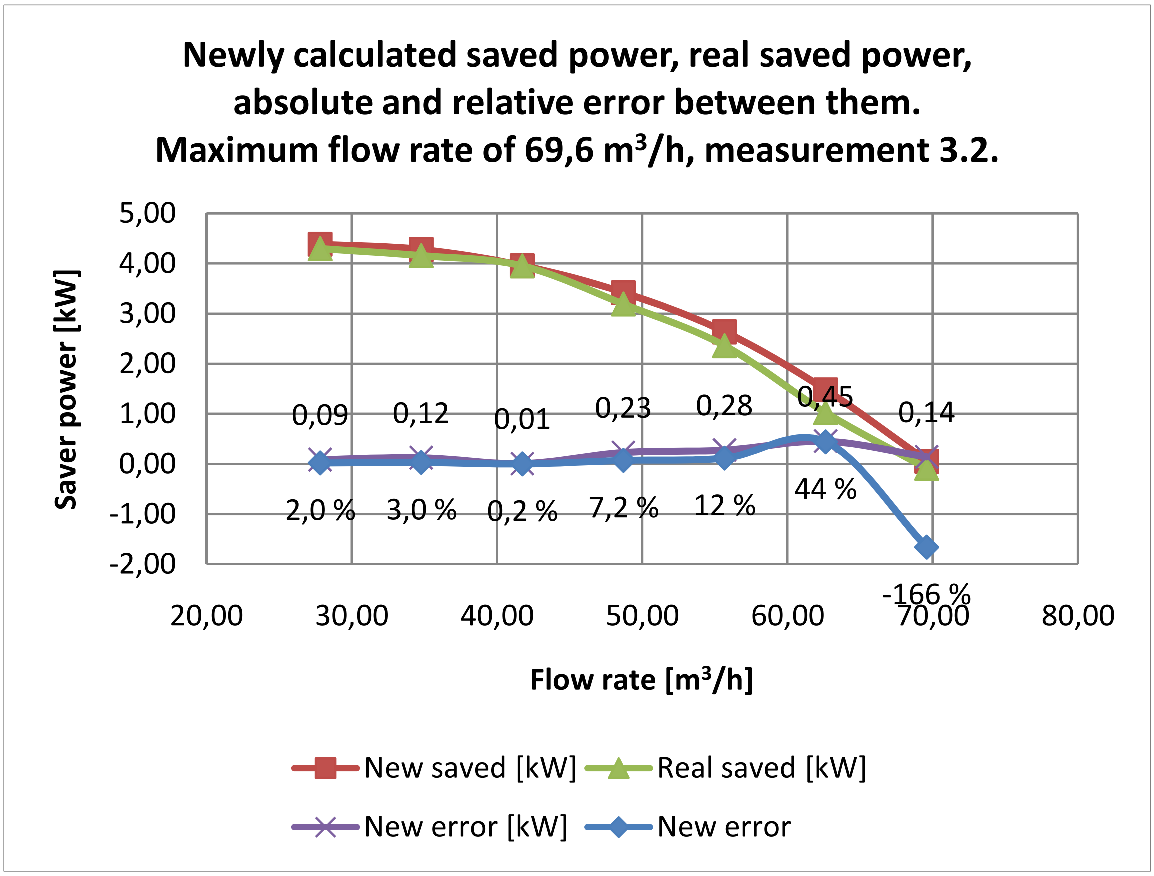
Flow rate		**Saved power**			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	69,60	0,10	-0,36	-129 %	± 98 %
90 %	62,64	1,64	1,11	49 %	± 22 %
80 %	55,68	2,60	2,27	15 %	± 8,8 %
70 %	48,72	3,38	3,20	5,7 %	± 5,9 %
60 %	41,76	3,94	3,90	1,2 %	± 4,7 %
50 %	34,80	4,26	4,20	1,6 %	± 4,4 %
40 %	27,84	4,39	4,39	0,0 %	± 4,1 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗



Newly calculated saved power, real saved power, absolute and relative error between them. Maximum flow rate of 69,6 m^3/h, measurement 3.1.

Newly calculated saved power, real saved power and relative error between them. Maximum flow rate of 69,6 m^3/h, measurement 3.2. The error margins in the table below are percentages of the measured values except for the error margins of error which are absolute values meaning that for example the -166 % error could be anything between -663 % and 301 %.

Flow rate		Saved power			
Flow rate	Flowrate [m^3/h]	New saved [kW]	Real saved [kW]	New error	Error margins:
100 %	69,60	0,06	-0,08	-166 %	± 467 %
90 %	62,64	1,48	1,03	44 %	± 23 %
80 %	55,68	2,64	2,36	12 %	± 8,3 %
70 %	48,72	3,42	3,19	7,2 %	± 6,0 %
60 %	41,76	3,96	3,95	0,2 %	± 4,6 %
50 %	34,80	4,28	4,16	3,0 %	± 4,4 %
40 %	27,84	4,38	4,30	2,0 %	± 4,3 %
Error margins:	± 2 %	± 5,1 %	± 13 %	⇨	⇗



Newly calculated saved power, real saved power, absolute and relative error between them. Maximum flow rate of 69,6 m^3/h, measurement 3.2.