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Optimising pump systems

1. Metrics

1.1 Pump performance and benchmarking studies for water utilities

Various metrics are in use, or have been proposed, for measuring the energy efficiency of pumps and pump systems, and for performance benchmarking. See for example references 2-4.

Reference 2 describes a large-scale pump performance and efficiency testing program in Ontario (Canada), with 152 water pump tests *by the thermodynamic method* in 41 pump stations, using Robertson Technology's P22 portable pump monitor. Data was collected in 2011 and 2012, and the resulting statistical analysis of the data showed that the PEI metric results in a much narrower variation than Specific Energy.

Reference 3 describes pump energy efficiency benchmarking in Australia, with data collected *by the conventional method* from 128 water and sewerage pump stations, using the PEI metric described in Reference 2. Data was collected in 2013 and 2014.

Reference 4 is progress reports from the ongoing (2017) Water Research Foundation (USA) project 4621, "Performance Benchmarking of Pumps and Pumping Systems for Drinking Water Utilities", with data collected to date *by the conventional method* from 148 pumps in 42 pump stations, mostly in the USA, but also from Canada, Australia, New Zealand, and Spain. These reports are available to WRF subscribers (most water utilities in the USA, Canada, and Australia).

1.2 Specific Energy metric

Specific Energy = Electrical Energy (E) / Quantity (Q)
The units employed vary with location and custom, but may for example be kWh/ ML. Electrical energy is measured from the integral of electrical power (kW) and time. Quantity is measured from the integral of flow rate (e.g. L/s) and time. The lower the value of Specific Energy, the better the nominal energy efficiency. However, as shown in Ref 1, Specific Energy generally decreases as flow rate increases, and a low Specific Energy could be an indication that a pump is operating outside of the Preferred Operating Range

(POR), resulting in a lower MTBF (Mean Time Between Failures) and higher maintenance costs.

1.3 Pump Energy Indicator (PEI) metric

This has more recently been called the 'Pump Performance Indicator –TDH' (Ref 3), to better distinguish it from a similar metric, and is calculated based on the pressure difference (Total Dynamic Head, TDH) across the pump:
PPI_{TDH} = kWh / (ML * m) (TDH)

PPI_{TDH} depends primarily on the pump efficiency of each operating pump, at the operating point, since for each pump:
$PPI_{TDH} = \rho*g*F / (\eta*M_E)$, where, in SI units
η is the pump efficiency (expressed as a fraction)
M_E is the motor and drive efficiency (expressed as a fraction)
ρ is the fluid density, in kg/ m^3, a function of fluid temperature and pressure
g is the acceleration due to gravity, in m/s^2
F (= 1/3,600) is a scaling factor from SI units to the units in which PPI_{TDH} is generally expressed, kWh/ML/m

The value of the metric will vary with pump efficiency, which in turn will alter depending on the pump operating point. If the discharge valve is partially closed, or if other pumps are operated in parallel, the operating point will move more to the left of the pump curve.

As pump efficiency can vary (due to both degradation, and shift of operating point) by more than an order of magnitude greater than motor and drive efficiency, it is the main parameter that determines PPI_{TDH}.

When the pump and motor efficiencies are set to 1, ρ is approximately 1000 kg/ m^3; g = 9.81 ms^{-2}, and the minimum value of PPI_{TDH} = 1000 * 9.81 / 3,600 = 2.725. As pump and motor efficiency become less efficient, PPI_{TDH} will increase.

1.4 Accuracy of measurement of metrics

The accuracy with which these metrics can be measured, by the conventional method, depends on the accuracy of the flow rate and electrical power meters, and pressure sensors.

In the Water Utility sector, in particular, pump stations may not have any flow metering, or just be equipped with a single station flow meter. If using a station flow meter to assess the performance of a single pump, it may be necessary to progressively close a discharge valve to shift the operating point to avoid high flow cavitation, and to obtain data for that pump at flow rates where other pumps may be operating in parallel. Where variable speed drives are fitted to pump motors, the speed may be varied instead.

Either way, with the conventional method, it is not possible to determine the contributions of individual pumps to the energy efficiency of a pump combination, at a particular operating point.

Another factor is the accuracy of conventional installed or strap-on flow meters, which may typically be 5% to 10%, due to a number of site-dependent errors of unknown magnitude. It is rare for the calibration of flow meters to be regularly checked in situ, as this requires accurate volumetric measurements in a large storage tank. The user is reliant on the manufacturer's calibration, often carried out many years ago and under completely different conditions. Flow meter accuracy is affected by air entrainment, cavitation, operating point, build-up on pipes and sensors, and pipe work configuration (often requiring long lengths of straight pipe before and after the flow meter). On-site recalibration methods may not be particularly accurate.

Electrical power measurement capability and accuracy varies widely, also bearing in mind that higher power pump motors require a 3-phase supply. Some pump stations have accurate electrical power measurements (better than 1%) for each pump. Others may only have very basic metering (5 to 10% accuracy).

The accuracy of installed pressure sensors also varies widely.

The above limitations will lead to corresponding errors in the calculation of metrics, and will possibly be too high for accurate measurements of energy savings, or for identifying improvements.

An indication of the scale of the problem is found from the large amount of data filtering that was employed in Refs 3 and 4, which used the conventional method for pump performance measurements.

In contrast, the data obtained by the thermodynamic method (Ref 2) was much more consistent.

When searching for ways to assess and improve the energy efficiency of a pump system, best practice would be to measure the contributions from the individual pumps by the thermodynamic method, and to monitor continuously, to cover all operating conditions. Robertson Technology's MicroPM™ pump monitor can be fitted to all pumps in a pump system, and provides all the information required.

2. Measuring and monitoring the metrics of individual pumps without the requirement for flow rate or power meters

Robertson Technology has a thermodynamic method for measuring and monitoring the energy efficiency of individual pumps, without the requirement for flow rate or power meters.

Pump parameters are summarised by the following well-known Pump Equation:
$\eta_p*M_E*P_W = q*\rho*g*H$ ....(1)

Metric units are employed in the following description, but US units can alternatively be selected.

The left-hand side of equation (1) is the electrical power (joules per second) applied to the fluid, after losses in the motor drive and pump: -
η_p is the pump efficiency (expressed as a fraction)
M_E is the motor and drive efficiency (expressed as a fraction)
P_W is the electrical power to the motor (in watts)

The right-hand side of equation (1) is the energy per second imparted to the fluid, and also has the units of watts (joules per second): -
q is flow rate, in m^3/s
ρ is the fluid density, in kg/m^3, a function of fluid temperature and pressure
g is the acceleration due to gravity, in m/s^2
H is pump total head, in m

Re-arranging equation (1), $P_W / q = \rho*g*H / (\eta_p*M_E)$
With appropriate scaling factors for the units employed, therefore, we can derive the following equations for the commonly used metrics:

Specific Energy: $E/Q = \rho*g*H / (\eta_p*M_E)$

Pump Performance Indicator (TDH): $PPI_{TDH} = \rho*g / (\eta_p*M_E)$

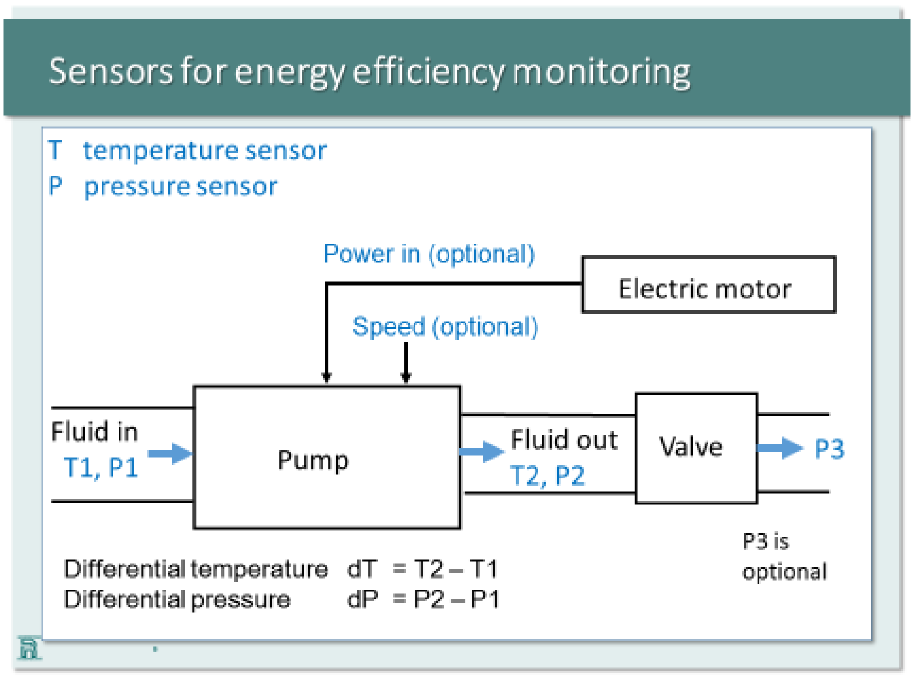
Flow rate and power do not appear in the right-hand side of these equations. The main variable in all the equations is pump efficiency (η_p). The higher the pump efficiency, the lower (and better) the Pump Performance Indicator.

Our method is firstly to calculate to calculate the pump efficiency (η_p) by the thermodynamic method, using temperature and pressure sensors (as for example described in the international standard ISO 5198) and secondly, to use this pump efficiency value directly in the derived equations for the metrics.

The other parameters on the right-hand side of the equations are readily known or measured. For example, H can be measured using the same pressure sensors employed for the thermodynamic pump efficiency measurement. ρ and g are obtainable from reference tables. M_E is obtained from information supplied by motor and drive manufacturers.

In this way, the energy efficiency of individual pumps can be measured accurately and easily. With continuous monitoring, key metrics can be accurately obtained for all operating pumps and operational conditions. Opportunities for energy efficiency improvements can be readily identified.

One implementation is by appropriate firmware in Robertson Technology's MicroPM Pump Performance Monitor, which calculates the pump efficiency to typically 0.5% accuracy by the thermodynamic method, using temperature and pressure sensors. These monitors can be fitted to every pump, in a pump system, for continuous monitoring. Taking into account the errors in the other parameters, the metrics are therefore measured to an accuracy of typically 1%.



3. Measuring and monitoring the metrics for complete pump systems

If power P_W for each pump can be measured, to reasonable accuracy, then the flow rate can also be derived, for every pump. Re-arranging Equation (1):
$q = \eta_p * M_E * P_W / (\rho * g * H)$

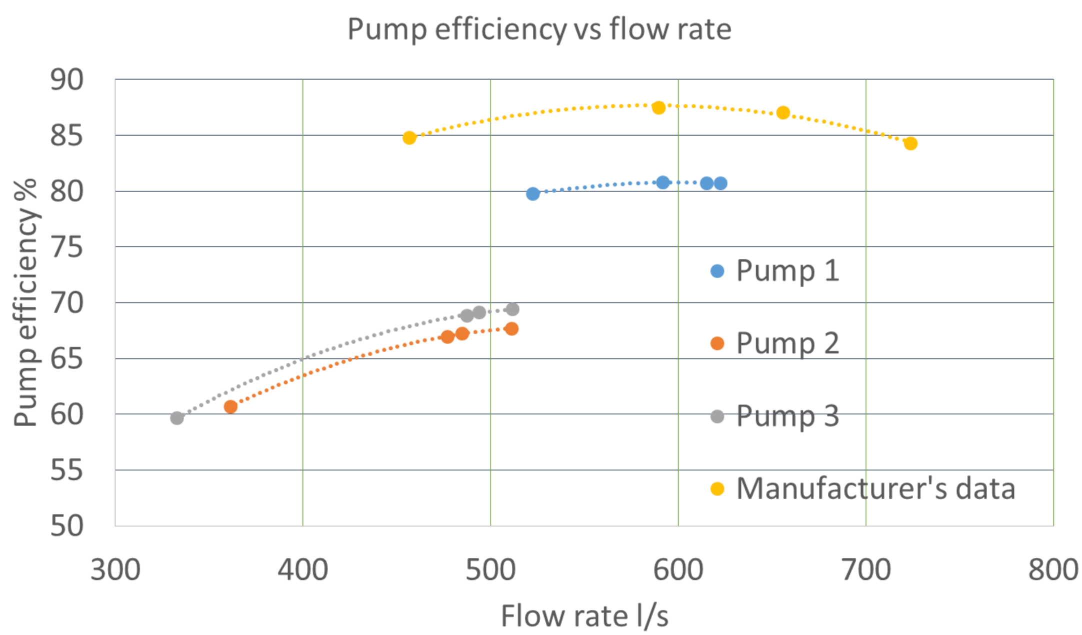
Having the flow rates for each pump allows totalisation, to accurately obtain the metrics for the complete pump system. Totals for the operating pumps in a pump station can be obtained by separate manipulation of the individual data, for example, in a PLC/ SCADA system, or with Robertson Technology's Micro Station Monitor.

4. Strategies for improvements to energy efficiency

4.1 Rapidly identify excessive wear with continuous monitoring

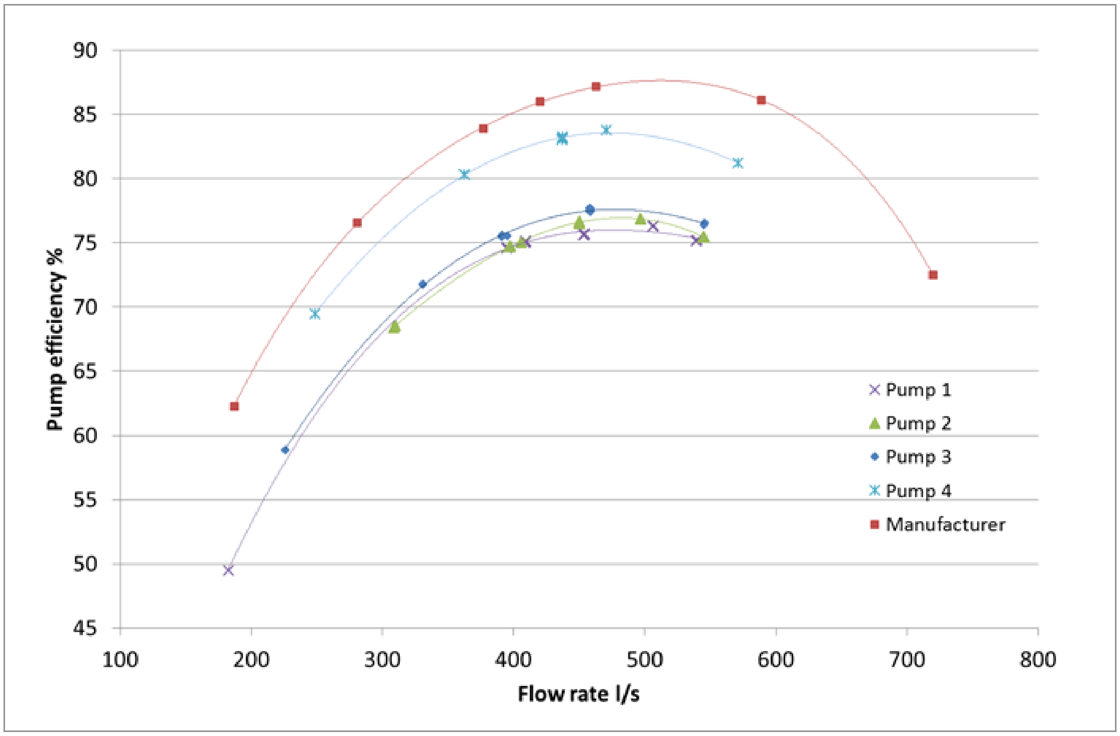
Failing to quickly identify problems is expensive.

Case study 1, Australia: 3 * 800 kW pumps in parallel; no efficiency monitoring



Wear ring problems with pumps 2 and 3. Without continuous monitoring of pump and energy efficiency, it was more than 6 months before the problem was noticed. Pump 1 was operating at 0.387 kWh/kl. Pumps 2 and 3 were operating at about 0.46 kWh/kl. Higher cost of running Pumps 2 and 3, relative to Pump 1, was US$92,000 over a 6 month period. Continuous efficiency monitoring is planned.

Case study 2, Australia: 4 * 600 kW pumps in parallel; no efficiency monitoring



The 3 most operated pumps rapidly lost efficiency. The problem was not identified for 10 months. Cost not quantified, but in excess of US$100,000

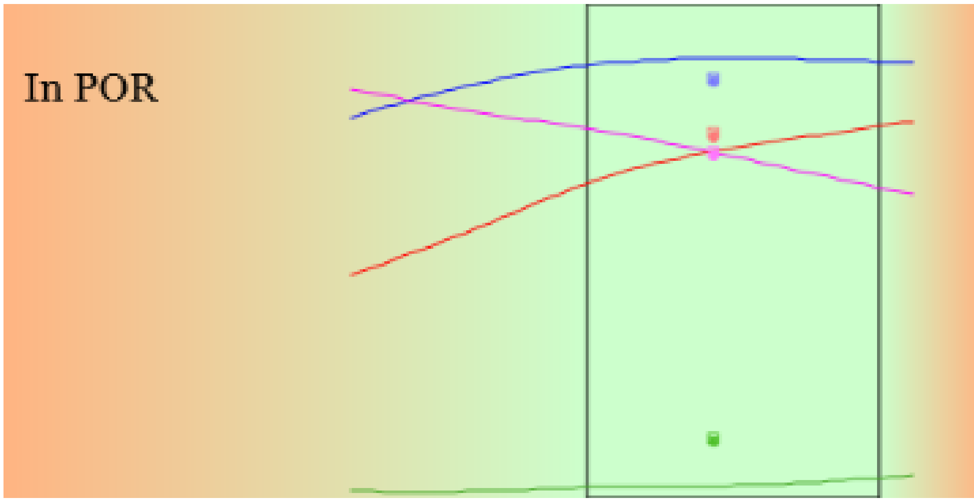
4.2 Ensure pumps and pump combinations are operating near the BEP (Best Efficiency Point), and within manufacturer's POR (Preferred Operating Region)

Operate pumps within the Preferred Operating Region to maximise pump efficiency. For example, with Robertson Technology's MicroPM Pump Monitor (MicroPM), with the power measurement option (to obtain flow rate), all relevant information can be logged and displayed.

The data for each pump can be automatically compared with manufacturer's data, to check that it is operating within expected parameters. For a real life example, see the section (below) from an embedded webpage, which provides a graphical 'at-a-glance' summary of pump performance. The X-axis is flow rate, and there are 4 parameters displayed on the Y-axis:

- Pump efficiency (blue) – a slight fall here
- Total dynamic head (pink) – spot on
- Electrical power (red) – increase due to loss in pump efficiency
- NPSHa (green) – well above the requirement

	Flow	Eff	Head	Power	NPSHa	BEP%
Actual Data	1012.87	85.14	245.88	2962.30	42.93	
Scaled Data	1012.9	85.1	245.9	2962.3	42.9	-2.8



Cursor xxxxx l/s xxxxx % xxxxx m/m xxxxx kW

BEP flow - 1042.40 , POR - 833.92 to 1250.88

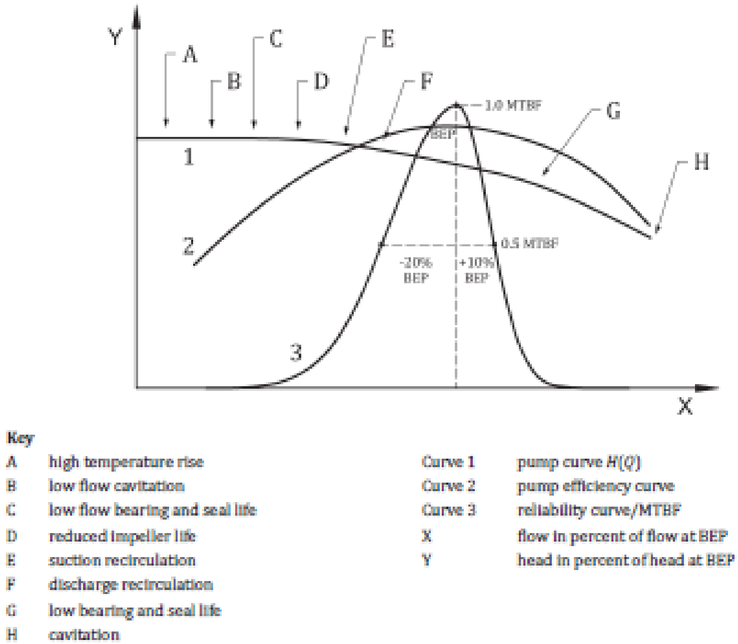
The operating point of this pump is close to perfect, it is within the POR, and only -2.8% lower than the Best Efficiency Point (BEP) flow rate.

The curves are manufacturer’s data, and the coloured dots show the current operating point. The two vertical lines define the Preferred Operating Range (POR), which is typically the flow rate at the BEP -20% and +10%.

Actual data is also scaled to a manufacturer’s speed, using the affinity laws. Here, the data is for a fixed speed pump and the scaling factors are unity. A cursor can be moved over the graph to obtain real values, in place of the xxxxx shown above.

According to ISO/ASME standard 14414-2015 “Pump system energy assessment”, the vertical lines define the points at which the Mean Time Between Failures (MTBF) is cut in half, compared with a maximum value at the BEP. Operating outside of these limits rapidly increases the probability of pump failure, cavitation, and recirculation, and reduces the life of bearings and seals (see section 4.3).

4.3 Consider maintenance costs as well



Operate near the Best Efficiency Point to minimise both energy and maintenance costs

Extract from ISO/ASME standard 14414-2015 (Pump System Energy Assessment)

4.3. Pump scheduling - Select the best combination of pumps to meet demand for lowest possible cost

This applies when there are more pumps available than required to meet demand.

<u>Case Study 3, USA: 6 * 2 MW pumps in parallel; continuous efficiency monitoring</u>

Pump	Efficiency %
1	81.6
2	81.3
3	87.6
4	83.9
5	89.1
6	86.4

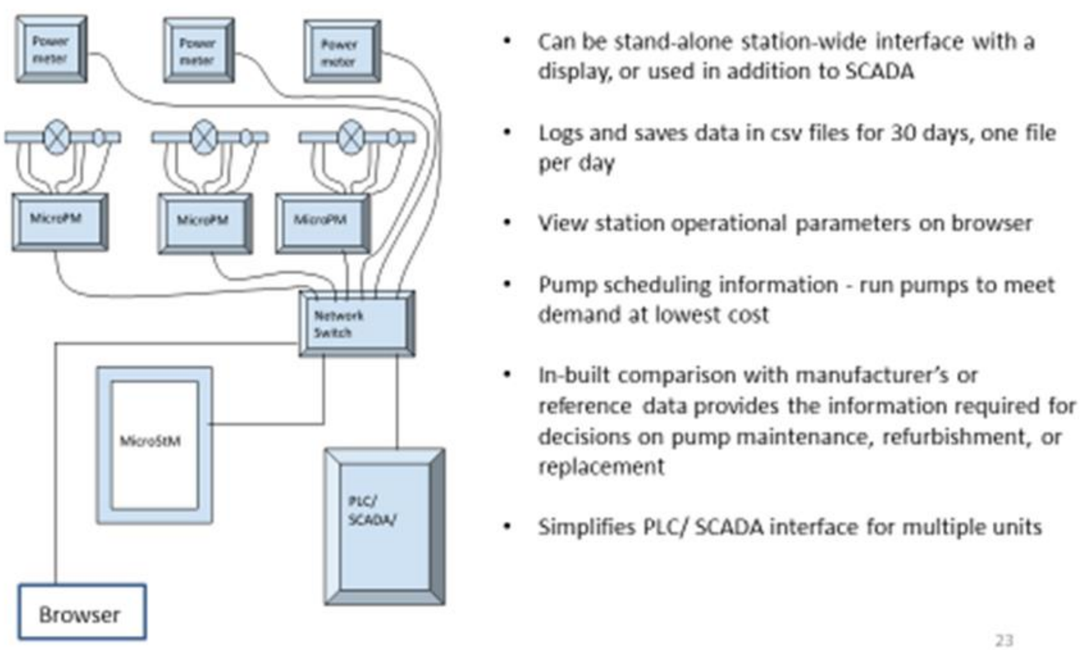
There are 7.8 percentage efficiency points between highest and lowest efficiency pumps. Savings by running the 3 most efficient pumps (average 87.7% efficiency compared with average 85% efficiency for all 6 pumps):
3 (no of pumps)* 0.027 (efficiency improvement)* 4,000 (hrs per year) * 2000 (average kW) * 0.08 (cost per kWh) = US $51,840 per year

Pump scheduling functionality provides information on which station pumps could be run to provide a required station demand at the lowest cost. These decision could be made by appropriate development of SCADA software, but the work required is quite complex and development and maintenance costs would be substantial. Robertson Technology's solution is to supply a separate Micro Station Monitor (MicroStM). The scheduler functionality is configurable for a given station/operational needs.

In-built comparison with manufacturer's or reference data provides the information required for decisions on pump maintenance, refurbishment, or replacement.

The layout below is shown with 3 pumps but there is no practical limit to the number of pumps in a given installation. The power meters shown in the schematic would not be required if active kW for each pump could be provided from existing power meters via SCADA. Optional pressure sensors to give the pressure drop across the discharge valves are also shown.

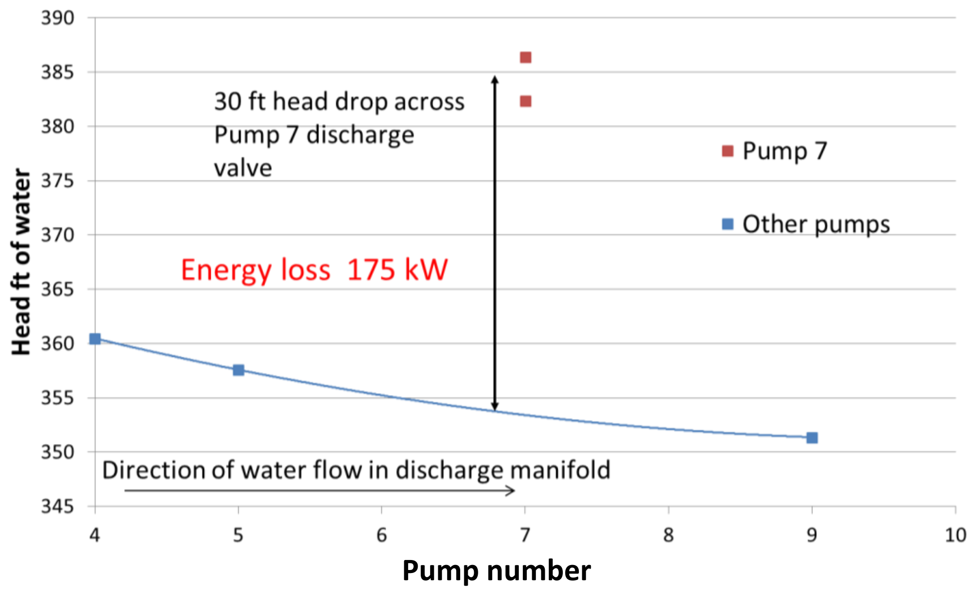
Station level operational parameters are also calculated and presented on the same interface.



4.4 Rapidly identify discharge valve problems

Significant amounts of energy can be lost across valves

<u>Case study 4, USA: 6 * 2 MW pumps in parallel; continuous efficiency monitoring</u>



Savings by identifying valve problem: 175 (kW) *0.10 (cost per kWh)* 2000 (hrs the pump was run per year) = US$35,000 per year

Robertson Technology's MicroPM Pump Monitor has a sensor option to measure the pressure drop across the discharge valve.

4.5 Check for back-leakage through the non-return valve (NRV) of a pump which is not operational

See section 6.6

5. Example of continuous monitoring, USA

23 pumps in 7 pump stations equipped with Robertson Technology's MicroPM Pump Monitor (including power and flow rate measurement)

The primary driver for purchase was accurate flow metering for each pump, to improve operational efficiency for water distribution. Such benefits have not been quantified, but some costs, for unnecessary pumping, must have been avoided. Case Studies 1 and 4 above are from one of the pump stations. Data has also been useful for identifying the onset of cavitation, as these pumps can suffer from high flow cavitation.

Temperature and pressure probes fitted to the discharge side of a pump

The characteristics of thermodynamic flow meters are:

- Long term reproducibility typically 0.5%
- Calibration of temperature, pressure, and power transducers sensors can be checked on-site
- Each pump has its own flow meter

- Independent of velocity profile, pipe configurations, build-up, cavitation, and air entrainment
- Long sections of straight pipe not necessary
- *Lower cost than alternatives for retrofitting to existing pump stations*
- *Low construction and pipe work costs for new pump stations*

6. Quantifying performance and the potential for improvements

6.1 Limitations of metrics

Metrics are used for comparisons with other pump stations, for performance benchmarking purposes, but they do not quantify the possible improvements which could be made in a specific pump station. Here we show how this can be done, using the MicroPM.

6.2 Single pumps

The condition of each pump and potential for improvement can be quantified by comparing actual PPI_{TDH} at the pump operating point with the maximum possible value PPI_{TDHMAX} that would be achieved if the pump was operating at the manufacturer's pump efficiency (η_{max}) at the Best Efficiency Point (BEP).

For each pump
$PPI_{TDH} = \rho*g*F / (\eta*M_E)$ and $PPI_{TDHMAX} = \rho*g*F / (\eta_{max}*M_E)$

Assuming that motor and drive efficiency are stable, we can define RE (relative efficiency factor for the pump):
$RE = PPI_{TDHMAX} / PPI_{TDH} = \eta / \eta_{max}$

RE will be 1 when the pump is operating at the BEP with no loss in efficiency since manufacture. Generally there will be some loss in efficiency with time, and the pump may be operating away from the BEP, so RE will be less than 1. The lower the value of RE, the higher the potential for improvement. RE is thus an intuitive metric for quantifying pump performance, and potential improvements. At any operating point, η and flow rate q for the pump can be found by the thermodynamic method.

6.3 Pump systems

The PPI_{TDH} values can be summed, weighted for individual flow rates, to obtain the average values for parallel pump systems.

PPI_{TDH} (n operating pumps) = $\rho*g*F / (\eta_{av}*M_E)$, where η_{av} is the average pump efficiency for the pump system, weighted for flow rates. Total q is the sum of the flow rates for all operating pumps.

Similarly, $PPI_{TDHMAXAV}$ (n operating pumps) = $\rho * g * F / (\eta_{maxav} * M_E)$ where η_{max} is the average manufacturer's pump efficiency, weighted for flow rates.

RE (system) = PPI_{TDHMAX} / PPI_{TDH} (n operating pumps) = η_{av} / η_{maxav}
$\eta_{av} = \eta_1 * q_1$ / (Total q) + η_2 * (q_2 / (Total q) + η_n * (q_n / (Total q)

At any operating point, η and q for each pump can be found by simultaneous measurements on each operating pump, by the thermodynamic method.

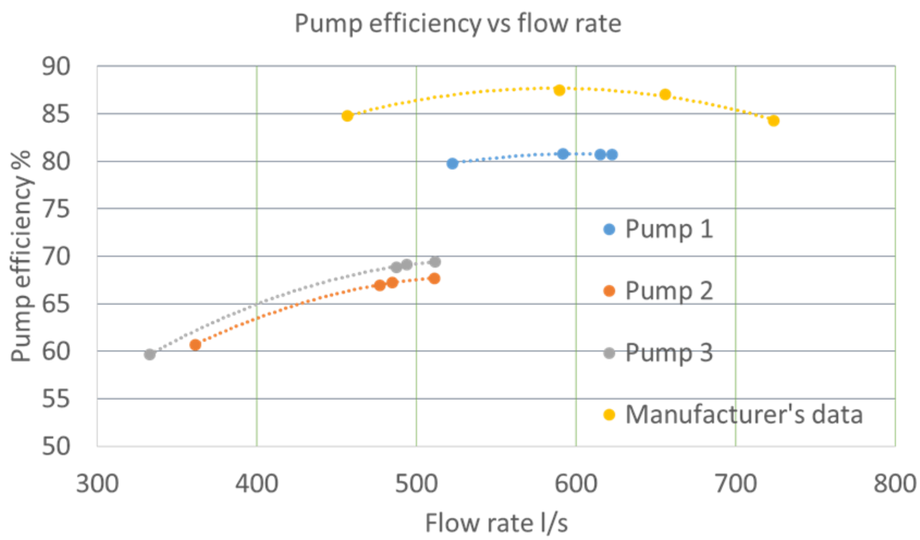
η_{maxav} can be obtained from manufacturers' data, by using the pump efficiency and flow rate at the BEP (Best Efficiency Point) for each pump. If all new pumps are nominally identical, to a first approximation, η_{max} and the average of all operating pumps will be the same for all pumps.

The RE, and the potential for improvements to the performance of individual pumps in a pump system can then be obtained. Continuous monitoring provides information for all operational conditions, and rapid advice of degraded performance.

Combinations of series and parallel pumps can be evaluated by first averaging pumps in series (which have the same flow rate through them), and then the parallel combinations. Motor and drive efficiency could be retained in the equations, in which case RE is the ratio of overall efficiency (wire-to-water) to maximum possible overall efficiency.

6.4 Case study, Australia (see also section 4.1)

3 * 800 kW pumps in parallel, 2 pumps badly degraded



Pump efficiency η and ML were measured simultaneously for every pump, by the thermodynamic method.

Pump	Pump efficiency η (open valve)	Flow rate l/s	Fraction of total flow rate	η_n * q_n / Total q
1	0.808	592	0.380	0.380 * 0.808 = 0.307
2	0.670	477	0.307	0.307 * 0.67 = 0.206
3	0.689	487	0.313	0.313 * 0.689 = 0.216
Total		**1556**		**η_{av} =0.729**

Manufacturer's fractional nominal pump efficiency at BEP η_{maxav} : 0.875
RE (system) = 0.729/0.875 = 0.833

The pump system is operating at an efficiency (1-0.833)*100 % = 16.7 % lower than its' potential. Pumps 2 and 3 are obvious candidates for refurbishment, after which post-refurbishment thermodynamic measurements will quantify the improvement.

6.5 Effect of pressure drop across discharge valve

If a discharge valve is partially closed, or faulty, so that a pressure drop occurs across the valve, then there will be some energy loss at the valve. The pump will be operating further to the left of the curve. This will be reflected in a lower value for RE. Pressure sensors before and after the discharge valve can provide the pressure drop across the valve.

6.6 Effect of back-leakage through the non-return valve (NRV) of a pump which is not operational

Back-leakage could be identified by comparing data from a separate station flow meter (if fitted) with the thermodynamic flow rate measurements for a matrix of operating pump combinations. When a pump with a defective NRV is not operating, the station flow meter will be reading proportionately lower than the summed thermodynamic flow rates for operating pumps, compared with when the pump is operating, due to losses through the NRV.

A note of caution though, most types of station flow meters (e.g. electromagnetic) could read high in the presence of cavitation or air entrainment.

6.7 Components of the fall in RE

There are two components, firstly, that due to the operating point being away from the BEP, and secondly that due to wear and other factors such as air entrainment, cavitation, and recirculation. Separate ratios can be used to quantify them, multiplying together to obtain the RE.

Robertson Technology's MicroPM™ continuous pump performance monitor can provide this information, since the manufacturer's pump efficiency data at the operating point is also obtained.

7. Requirement for accurate temperature measurement, when using the thermodynamic method

There are two main factors to be aware of:

(1) *The accuracy and stability of calibration of the temperature probes themselves* (see Robertson MicroPM temperature probes).

The general specification that Robertson Technology works to for differential temperature (dT) measurement is a long-term calibration accuracy of < 0.001 °C (0.0018 °F) for 10 years. This permits accurate continuous monitoring for total heads above about 12 m (40 ft), see the table below:

% change in pump efficiency, for a 0.001 °C variation in dT

Head, m of water	Pump efficiency, %		
	70%	80%	90%
12 m (40 ft)	2.4	2.8	3.0
25 m (82 ft)	1.2	1.4	1.5
50 m (165 ft)	0.6	0.6	0.8
100 m (330 ft)	0.3	0.3	0.4

As well as the calibration stability, each temperature probe has two temperature sensors, operating independently. This provides additional real time confirmation that the temperatures being measured are indeed in specification. In the unlikely event that a temperature measurement issue is detected, an alarm is generated.

(2) *For continuous monitoring, the method used to insert the temperature probes to take the measurement*.

Robertson Technology have developed a temperature measurement approach specifically for long reliable life in continuous monitoring situations. Short, low mass thermowells are used with redesigned temperature probes essential for accurate and continuous measurements, to minimise vibration heating, mechanical stress, and stem effect.

Note that when testing with portable units, compromises are often made, and immersion temperature probes may be inserted into the fluid via gate or ball valves, rather than via thermowells. This method is prone to measurement error due to vibration heating. If used for continuous monitoring, the mechanical stresses will eventually lead to metal fatigue and fracture of the temperature probes.

8. References

1. Robertson, M., Rhodes, I. (2008). Optimising and Verifying Energy Savings in Pumps and Pumping. *4th International Conference on Water and Wastewater Pumping Stations*. Cranfield, Bedfordshire, UK.

2. Pump Energy Efficiency Field Testing & Benchmarking in Canada
Paper presented by Fabian Papa and Djordje Radulj (HydraTek & Associates Inc), Bryan Karney (Faculty of Applied Science and Engineering, University of Toronto), Malcolm Robertson (Robertson Technology Pty Ltd) at Asset Management for enhancing energy efficiency in water and wastewater systems, International Water Association, Marbella, Spain, April 2013 (available as a download)

3. AUSTRALIA-WIDE PUMP ENERGY EFFICIENCY BENCHMARKING DEMONSTRATES OPPORTUNITIES FOR IMPROVEMENT, OzWater 2015 (Australian Water Association)
Daniel Livingston 1, George Charakos 2, Chris Farragher 1, Jennifer Bartle-Smith 3, Kris Robinson 4, Murray Dancey5
1. Hunter Water Corporation, Newcastle, NSW, Australia
2. Melbourne Water Corporation, Melbourne, VIC, Australia
3. Water Services Association of Australia, Melbourne, VIC, Australia
4. ACTEW Water, Canberra, ACT, Australia
5. Wannon Water, Warrnambool, VIC, Australia

4. Water Research Foundation Project 4621 "Performance Benchmarking of Pumps and Pumping Systems for Drinking Water Utilities"
See periodic reports (available to WRF subscribers) prepared by MWH (now part of Stantec), and Derceto, Inc (Suez SA). The principle investigator for Project 4621 is Mohammad Badruzzaman (MWH), and co-principle investigators are Joseph G. Jacangelo (MWH) and Simon Bunn, Derceto, Inc.