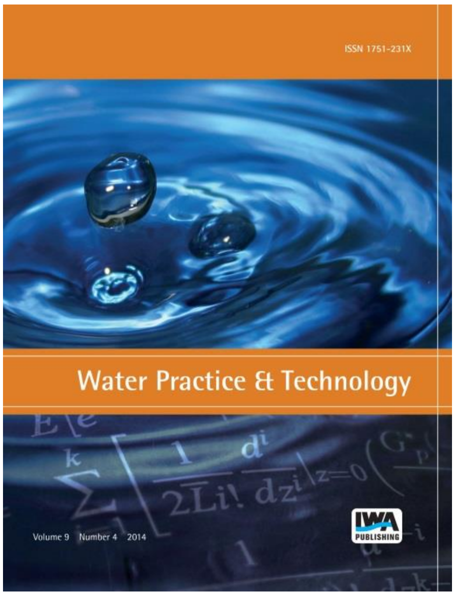

ISSN 1751-231X
Water Practice & Technology
Volume 9 Number 4 2014
IWA PUBLISHING

© IWA Publishing 2015
872
Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

Pumps: energy efficiency & performance indicators

Fabian Papa[a,*], Rita Cavaleiro de Ferreira[b] and Djordje Radulj[a]

[a] HydraTek & Associates, 216 Chrislea Road, Suite 204, Vaughan, Ontario L4L 8S5, Canada

[b] Asociación Nacional de Empresas de Agua y Saneamiento de México A.C. (ANEAS), Palenque 287, Col Narvarte, Deleg, Benito Juarez C.P. 03020, México, D.F.

* Corresponding author. E-mail: f.papa@hydratek.com

Abstract

Pumping is a central component to many water supply and distribution systems, and one which consumes significant amounts of energy. Increased attention to energy conservation is a common theme globally and, in the context of water supply systems, the need to understand the energy efficiency with which pumps operate *in situ*, and the opportunity to improve upon any inefficiencies, is becoming increasingly recognized. This paper discusses two separate and independently conceived and delivered initiatives that, while taking very different approaches to raising awareness and improving the industry's state of practice in this regard, are rather synergistic when viewed in a holistic sense. Recent work in Mexico is engaging the numerous utilities across the country to begin the measurement of pump energy efficiency, having wide-reaching impact, while work in Canada is exploring the details of individual pump performance through accurate field testing. Both these initiatives use a common approach to measuring performance of pump efficiency, based on the normalization of energy consumption relative to the output of the pump, namely the flow and total dynamic head delivered. The exact performance indicators used are somewhat different, but very closely related, and this paper explores the nuances of these differences in detail. As well, results from both the Mexican and Canadian experiences are presented, and guidance on the use of the performance indicators is provided.

Key words: pump efficiency, pump energy indicator, pump performance, pump testing, standardised energy consumption, thermodynamic method

INTRODUCTION TO PUMPING

Apart from salaries, energy costs are often the highest operating cost of a water and wastewater operator (utility), particularly for those systems that are not naturally blessed with a gravity supply of water and therefore rely on pumping. The amount of energy required for pumping water is, in turn, dependent on a number of factors including (but not limited to): (i) the vertical height water needs to be moved in order to extract it from the natural environment and to provide sufficient pressure to meet operational objectives; and (ii) the distance that the water needs to be transported from where it is sourced to where it is used. In addition to these energy requirements, the conversion of electrical power (i.e., what the pump uses) to water power (i.e., what we want from the pump) suffers from inefficiencies further increasing energy needs. The conversion of power is governed by the following expression:

$$P = \frac{\gamma \cdot Q \cdot H}{\eta} = \frac{\gamma \cdot Q \cdot H}{\eta_D \cdot \eta_M \cdot \eta_P} \tag{1}$$

where P is the input power to the pumping unit (kW), γ is the specific weight of water (9.81 kN/m^3),

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

Q is the flow rate through the pump (m^3/s), H is the total dynamic head (TDH, or lift) of the pump (m). The combination of these terms (i.e., $\gamma \cdot Q \cdot H$) is the water power discussed above and, in the absence of any efficiencies would equate to the input power. Further, what is wanted from the pump is its output, namely flow (Q) and TDH (H) and, any inefficiencies (which appear in the denominator) detract from how much of this output can be obtained for each unit of input power (P). The term η represents the overall electromechanical efficiency of the pumping unit which itself consists of: (i) an optional drive unit which moderates the electrical input to the motor to control the resulting rotation (e.g., Variable Frequency Drive or VFD, sometimes referred to as Variable Speed Drive or VSD); (ii) the motor which converts the electrical power input into a mechanical, rotational output; and (iii) the pump itself which takes the rotational input power from the motor and, through rotation of the pump impeller, applies this energy to the water passing through the pump by accelerating it. Each of these components has its own efficiency (i.e., η_D, η_M and η_P) with respect to energy conversion, but the single largest driver of overall electromechanical efficiency is the pump efficiency (η_P), both in terms of its absolute value as well as its potential range.

Both the drive efficiency (η_D) and motor efficiency (η_M) are generally quite high, on the order of 0.95 (or 95%) with some variation, yet the degradation in efficiency is generally quite small that it often suffices to apply the manufacturer's value for these. On the other hand, the nature of the physical energy transformation in pumps can cause significant deterioration in both performance (i.e., output) as well as the energy efficiency at which it operates. The reasons for this are many and complete treatment of this subject is beyond the scope of this paper, but it is fair to say that the physical interaction between the fluid and the pump's components is a major contributor. Moreover, the nature of this physical interaction is commonly influenced by how the pump is operated relative to its optimal range and phenomena such as cavitation can have massively detrimental effects on pump impellers and other components.

An example of a pump's performance characteristics is illustrated in Figure 1. This image represents the original manufactured condition of a particular pump, showing the relationship between power input required (P), total dynamic head (H) and pump efficiency (η_P) relative to the pump discharge (flow) rate (Q). Of particular interest to this paper is the shape and magnitude of the pump efficiency (η_P) curve, with a maximum value – known as its best efficiency point – as well as a range around it where efficiencies are generally quite high before they drop off. Also shown in the figure are the actual *in situ* curves as tested demonstrating the degradation in performance manifested as lower output heads, lower efficiencies and increased power requirements for each flow rate.

While it is generally understood throughout the industry that pump efficiency is an important consideration in relation to energy consumption, the actual understanding of the performance of pumps in operation is generally quite poor. As a result, there is little hard evidence upon which operators can rely to make improvements, either to the pump itself (e.g., refurbishment, component or unit replacement, etc.) or the manner in which it operates (e.g., when to use and under what system conditions). Often, the assumption is made that the original manufacturer's efficiency curve is appropriate to use, irrespective of the pump's condition, for purposes of hydraulic modelling and decision making. Clearly, the quality of any decision making is a function of the quality of the input parameters used in that process.

Accordingly, there is a need to understand the following:

- the potential magnitude of the inefficiency problem such that the appropriate level of priority can be assigned to its investigation;
- the reasons for the problem such that the root causes can be addressed, rather than the symptoms, in order to avoid future recurrence;
- the potential interventions that can be applied to effect improvements; and

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

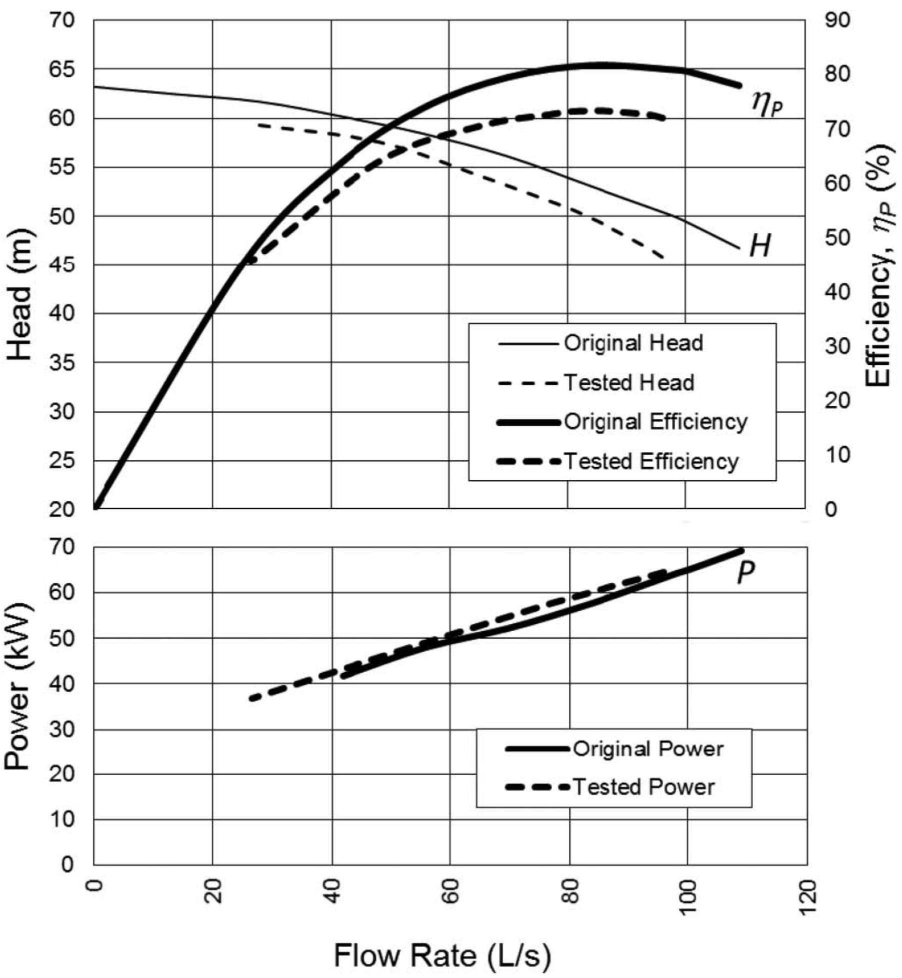

Figure 1 | Sample of original manufacturer's characteristic curves for pump with 75 kW (100 hp) motor compared with *in situ* tested curves (HydraTek 2013).

- the economics associated with the interventions and the expected value of the improvements (e.g., costs vs. benefits).

The subsequent sections speak to two independently conceived initiatives underway in North America that are tackling this subject from different angles, the interrelationship between these initiatives in a broader context, their results and other matters of interest including appropriate performance indicators and benchmarking metrics.

THE MEXICAN INITIATIVE

Mexico's association representing water and wastewater operators, ANEAS (Asociación Nacional de Empresas de Agua y Saneamiento), is implementing an initiative to sensitize the operators to the importance of pump energy efficiency. The motivation for the initiative is to encourage energy and financial savings and, while there are many opportunities for this in water and wastewater systems (e.g., water loss reduction, treatment process improvement, etc.), one of the most immediate and effective ways of achieving these savings is by understanding and improving pump efficiency, as well as controlling pump energy usage relative to the tariff structures and peak schedules.

This initiative, named CEEPA (Cálculo de Eficiencia Energética y Potencial de Ahorro en equipos de bombeo; or calculation of energy efficiency and savings potential in pumping equipment), is

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

reaching out to Mexico's vast number of operators and pumping stations to raise awareness and encourage the reduction of energy consumption. The first year of the initiative (2014) attracted participation from 9 operators providing service to 80 municipalities with data from 315 pumping stations. In 2015, the expectation is that up to 5,000 pumping stations will participate in the program, although it is worthy to note that the exercise is open to all Latin American water operators and the results are delivered in Spanish. The annual program is further divided into two phases: registration of operators for the initiative until June; and data collection, validation, analysis, report production, individual feedback, and publication of joint benchmarking data thereafter.

Methodology

Energy efficiency is calculated based on the IWA performance indicator Ph5 – Standardised Energy Consumption (Cabrera *et al.* 2011; Alegre *et al.* 2006) at both the individual pump level and at the operator level, based on the following expressions:

$$Ph5_{\text{pump}} = \frac{E_{\text{pump}}}{\frac{V_{\text{pump}} \cdot H_{\text{pump}}}{100\text{m}}} \tag{2}$$

$$Ph5_{\text{operator}} = \frac{\sum_i E_{\text{pump}_i}}{\sum_i \left(\frac{V_{\text{pump i}} \cdot H_{\text{pump}\,i}}{100\text{m}} \right)} \tag{3}$$

where *Ph5* is the standardised energy consumption of the pump (kWh/m^3/100 m) for either the pump or operator (as the case may be), E_{pump} is the energy consumption of a particular pump (kWh), V_{pump} is the volume of water processed by the pump (m^3), and H_{pump} is the TDH (or lift) delivered by the pump (m), all for a specified time period (typically one year, although for this initiative quarterly information is acceptable). The subscript i is used to identify the individual pumps in the summation calculations for each operator.

The information required to complete these calculations include the volume of water processed (lifted) over a given time period, the height to which it was lifted during that time period, and the energy consumed for the pumping activity during that time period. The results are often reported on an annual basis to allow for fair comparisons, although this is not necessarily a strict requirement. While seemingly straightforward, the lack of adequate instrumentation providing accurate data is commonplace and, in the absence thereof, estimations are required. For instance, in the absence of a flow meter, an estimate of volume based on pumping hours may be used, or an instantaneous measurement is taken as a longer-term average. If the TDH is not measured, the pump nameplate data or a mix of other estimations is used. In fact, obtaining data on the TDH is the biggest challenge. Most of the pumps are located in wells and are not equipped to measure dynamic water levels, and pump specifications are often lacking. Energy consumption data is typically available through an electricity meter or bill (and which may include the energy consumed by other devices or processes (e.g., ventilation, lighting, etc.) at any particular facility). For pumps operating at variable speeds, data for several modes of operation need to be estimated.

As one can appreciate, each of the above methods of estimation is subject to considerable error and is highly dependent upon the interpretation of information by the operator. With this in mind, the initiative's managers are careful to draw conclusions and to suggest further measurements as well as potential investments in improvements. Irrespective of the potential inaccuracies, there is value in all of the results obtained as it draws attention to the subject, encourages thought and dialogue within and amongst operators, thereby elevating the state of practice in general.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

CEEPA outputs and benchmarking as a tool for competition

The CEEPA initiative delivers individual reports for each operator identifying pumps as exhibiting 'good', 'medium' and 'bad' performance. The report also indicates the savings potential in terms of both energy costs (kWh), financial costs (Mexican Pesos, $MXN) and emissions (kg CO_2) assuming the pump would operate at a reasonable level of performance. This reasonable level of performance is based on matching the average tested results of the large-scale pump performance and efficiency testing program conducted in Canada and discussed later in this paper (HydraTek 2013). A sampling of these results is presented in Figures 2 and 3.

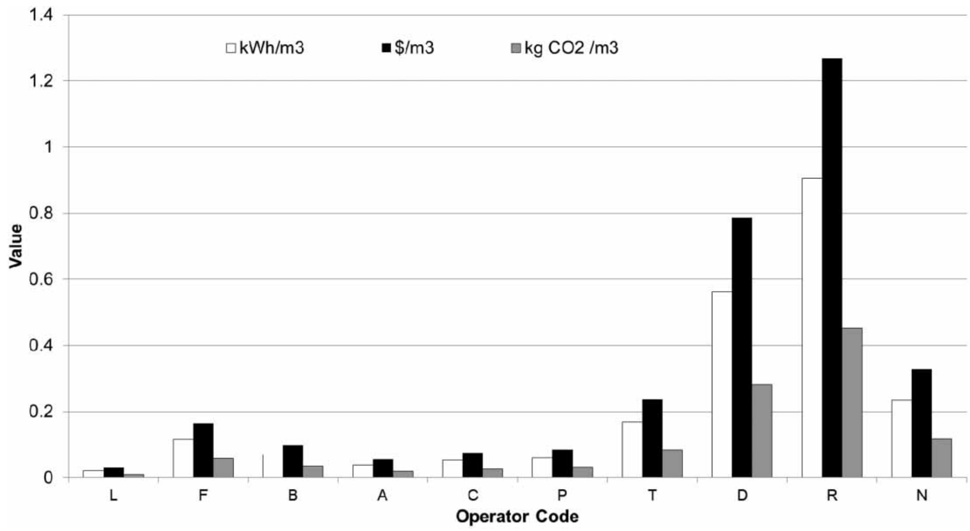

Figure 2 | Energy (kWh), financial ($MXN) and emissions (kg CO_2) savings potential per cubic meter for each operator (Olivares *et al.* 2015).

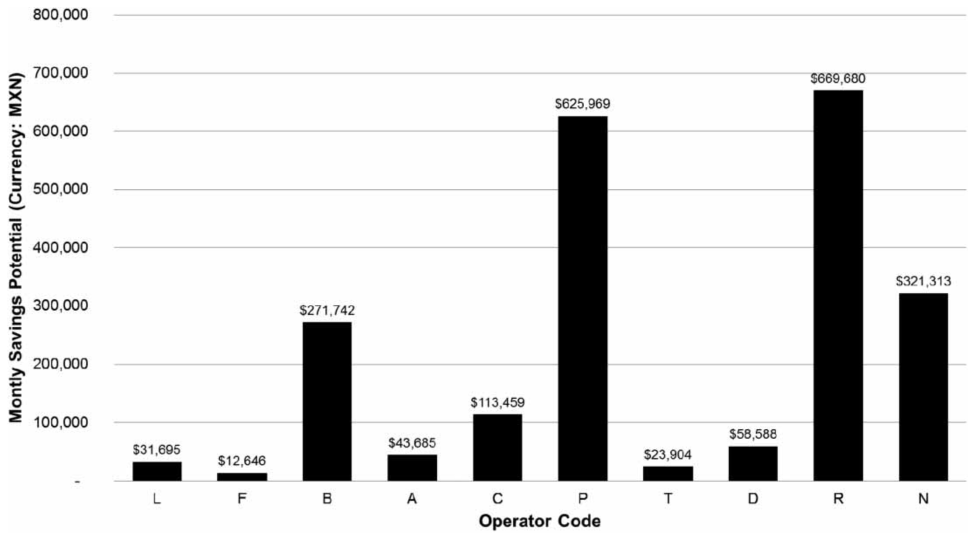

Figure 3 | Monthly electricity savings potential for each operator ($MXN; Olivares *et al.* 2015).

While some of the results are comparable, it is also evident that there is a wide range in results suggesting that certain operators either have extremely poor pump performance and efficiency operations with significant potential for savings or whose data quality is suspect. It is recognized that these

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

results may be suffering from various errors and uncertainties in the input parameters noted above, and while the results may not be accurate in an absolute sense, the results continue to be useful. That is, those operators that are clearly underperforming, whether in a real or perceived sense, at the very least now have the knowledge that this is a matter which warrants further consideration and effort, drawing attention to the need for improvement which, in turn, requires a sense of comfort with the information used to generate these results before making sizable investments in interventions.

In addition to the savings potential, CEEPA produces a benchmarking report (Olivares *et al.* 2015) which includes a ranking of the participating operators (see Figure 4). The purpose of the benchmarking exercise is to create a virtual competition in a market with otherwise monopolistic characteristics. The results can either be a source of pride for the operator which it can use to promote the level of its services to its directorship and customers, or be a source of concern leading to change for the better. Since participation in the CEEPA initiative is a voluntary act, the performance of each operator is kept anonymous in order to not affect the operator's public image, although each operator knows its position in the ranking. As an exception to this rule in 2015, those operators that receive federal funding in relation to this initiative will be identified for purposes of accountability.

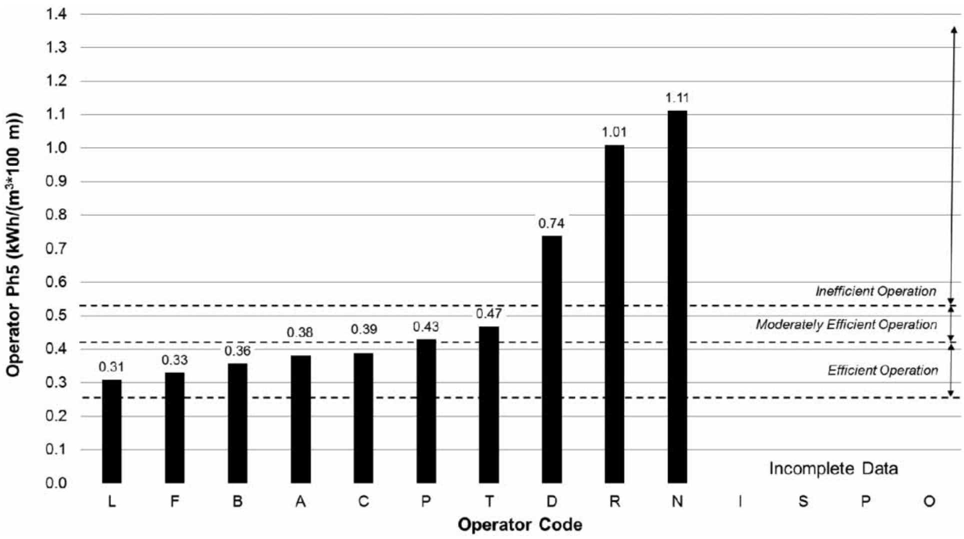

Figure 4 | Overall standardised energy consumption (Ph5) for each participating operator (Olivares *et al.* 2015).

Additional noteworthy points about CEEPA

The CEEPA initiative does not preclude the need for energy audits; rather, it is complementary. The CEEPA results represent wider work periods (up to 1 year) rather than instantaneous measurements typical of an audit. While the CEEPA results will not be as accurate as an energy audit, it does provide a reasonable filter to screen the relative performance of pumping equipment with fewer instrumentation needs, leading to lower monitoring costs than field energy audits. It also represents an important first step for operators towards the broader objective of energy monitoring and efficiency improvement.

In terms of benefits and the long-term perspective of the (somewhat massive) CEEPA initiative, the results stemming from this work assist operators in establishing priorities for additional efforts and actions to be taken, whether it be for pump refurbishment, replacement, operational adjustments, or to improve data collection and performance monitoring prior to undertaking such investments. Further, CEEPA is paving the way in Mexico for performance-based incentives for water operators.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

It will ease the transition to a time when energy efficiency reporting will be mandatory. Currently, new credit, subsidy and other incentive programs are being designed with Ph5 as the monitoring indicator for efficiency and, while the Ph5 performance indicator is well known in academic circles, it does represent an innovation for most water (and wastewater) system operators.

At present, Mexico is preparing its water sector reform where energy efficiency might have a place, considering its impact on operator finances and the highly emphasised efforts of the Mexican government towards climate change mitigation.

THE CANADIAN EXPERIENCE

From 2011 to 2013, a large-scale pump performance and efficiency testing program was carried out in Ontario, Canada's most populous province. This program was sponsored by the Ontario Power Authority's Conservation Fund, recognizing the need to encourage energy conservation in municipalities where a large amount of energy is consumed in the delivery of water, all of which is through pumping. A total of eight municipalities participated in the program, representing a cross-section of Ontario's geography, as well as a cross-section of municipality size. In total, 152 pumps were tested ranging from 22.5 kW (30 hp) to 3,000 kW (4,000 hp) in motor size. The delivery and results of this program achieved the objectives of raising awareness of the nature and magnitude of the energy losses through pump inefficiencies, as well as to support decision making for improvements founded in reliable data. This program was an excellent example of cross-sectoral collaboration between the public energy and water sectors (HydraTek 2013).

In fact, the nature of this testing work ties in well with the findings of the work in Mexico which noted that '(t)he magnitude of the inefficiencies is unknown due to the absence of a culture of registering and interpretation of data, and a lack of proper instrumentation to measure the operating parameters of the pumps' (Olivares *et al.* 2015). Here we begin to see the synergies between these independent initiatives which are discussed later in this paper.

Testing technology

There are two technologies available when it comes to testing pump performance and efficiency: (i) the conventional method; and (ii) the thermodynamic method. Only a brief description of each is provided here, and several additional resources are available (see HydraTek 2013).

The conventional method requires measurement of the input power to the motor's drive (e.g., VFD), if applicable, or more commonly the motor itself (P), the TDH of the pump (H) and the flow rate (Q). Combining these measurements with reasonable estimates of drive and motor efficiencies (i.e., η_D and η_M, respectively), then the efficiency of the pump (η_P) can be calculated using Equation (1) and, as such, is an indirect measurement of this parameter. This method is useful inasmuch as the flow measurements are accurate, being an issue which frequently arises when piping configurations, materials and accessibility constraints prevent the proper installation of flow metering devices.

The thermodynamic method similarly measures the input power to the motor's drive (e.g., VFD), if applicable, or the motor itself (P) and the TDH of the pump (H), however, it uses temperature measurements immediately upstream and downstream of the pump to determine the pump's efficiency directly. Observing the first law of thermodynamics (i.e., conservation of energy), this method recognizes that any input energy that is not converted into productive output energy, namely flow and pressure (head), is converted largely to thermal energy. Accordingly, this method requires that the temperature sensors be highly accurate (i.e., capable of measuring <1 mK) and stable.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

The thermodynamic method is generally recognized in the industry to be the more accurate of the methods, when applicable. For this study, 137 of the 152 tests employed the thermodynamic method alone, 15 of them employed the conventional method alone, and 57 employed both methods. The simultaneous application of both methods was useful in highlighting the differences between the methods.

TESTING RESULTS

While a number of useful statistics were derived from the results of this program, only a sample is provided here. Table 1 provides the fundamental results, showing the degradation of pump efficiency since original manufacture. The 'efficiency loss' identified in the table represents the difference between the peak efficiency of the pump in its *in situ* state at the time of the test relative to its original manufactured condition. The average efficiency loss of all pumps tested was found to be 9.2% (in absolute terms), a considerable amount. However, recognizing that pumps may not perform at or near their points of peak efficiency – the actual operating point of the pump is dependent upon its dynamic interaction with, and resistance received from, the system into which it pumps – the Overall Efficiency Gap represents the difference between the peak efficiency of the pump at the time of its original manufacture and the efficiency at which the pump typically operates. Accordingly, this difference is somewhat larger and the average of all pumps tested was found to be 12.7% (again, in absolute terms).

Table 1 | Results of pump performance and efficiency testing of 152 water pumps in Canada (HydraTek 2013)

	Average Pump Efficiency (η_P)	Average Wire-to-Water Efficiency (η)
Manufacturer's Best Efficiency Point (MBEP)	86.4%	81.4%
Tested Best Efficiency Point (TBEP)	77.2%	72.7%
Tested Typical Operating Point (TOP)	73.7%	69.4%
Efficiency Loss (η_{MBEP}–η_{TBEP})	9.2%	–
Overall Efficiency Gap (η_{MBEP}–η_{TOP})	12.7%	–

Other interesting results from the testing program relate to the financial analyses that were undertaken to support business cases for making intervention decisions. Again, this ties in well with the findings from Mexico which noted that, '(f)or making decisions involving investments, it is recommended that monitoring data is complemented by measurements rather than estimates of parameters' (Olivares *et al.* 2015). One of the useful results from the testing work in Canada is the comparison of pre- and post-refurbishment test results for two of the pumps in the program. Following completion of the program, additional pre- and post-refurbishment tests have comfortingly yielded comparable results. For these pumps, recoveries in efficiency loss (as defined above) of 65% and 71% were measured. These results are encouraging and importantly help to estimate the practical savings that may be considered when contemplating an intervention such as pump refurbishment, such that the savings may be weighed against the costs in order to justify the investment decision.

> 'If you don't measure what you are doing, you can't control it, if you can't control it, you can't manage it, if you can't manage it, you can't improve.'
>
> ~ Peter Drucker

Of course, pump testing is important for many more reasons than energy efficiency alone, and include matters such as operational management, asset management, hydraulic modelling, amongst many others.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

Benchmarking

A performance indicator was developed as part of this program, titled the pump energy indicator (PEI), which normalizes the power consumed by a pump against its output (i.e., flow and TDH) for the spectrum of flows for any given pump. This metric is closely related to the IWA's Standardised Energy Consumption (Ph5) performance indicator, and the difference is elucidated later in this paper as is the superiority of both these metrics to others available in the industry. Both of the Ph5 and PEI performance indicators are intuitively useful in that they provide immediate insight into the energy requirements (kWh) to deliver a certain quantity of water (m^3 or Mm^3) to a certain destination as measured in terms of both vertical elevation gain plus line friction losses (m). Accordingly, both high-level (Ph5) as well as detailed (PEI) assessments are facilitated to support decision making. Table 2 presents the PEI results for this program.

Table 2 | Statistics (averages) for PEI from Canadian Study (HydraTek 2013)

	PEI (kWh/Mm^3/m H_2O)
Manufacturer's Best Efficiency Point (MBEP)	3,350
Tested Best Efficiency Point (TBEP)	3,770
Tested Typical Operating Point (TOP)	3,980
Pump with the Best PEI @ TBEP	3,360
Pump with the Worse PEI @ TOP	4,970

FRAMEWORK FOR CONTINUOUS IMPROVEMENT

As noted earlier, both the Mexican and Canadian initiatives discussed above were conceived completely independently from each other yet there is a natural synergy between them and they have an important place in a broader framework for continuous improvement. This framework is illustrated graphically in Figure 5.

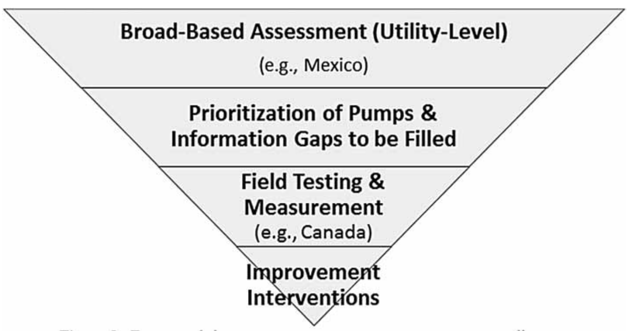

Figure 5 | Framework for continuous improvement in pump energy efficiency.

In the context of this framework, the initiative underway in Mexico can be viewed as a 'top down' approach to raising awareness and encouraging improvements in the industry, while the field testing and measurement work in Canada can be viewed as a 'bottom up' approach. Both approaches have their merits and have the strongest impact on effecting positive change when working in concert with each other.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

BENCHMARKING METRICS

The preceding discussions introduced the Ph5 and PEI performance indicators without consideration of any other metrics which might be considered and used in practice. This section briefly discusses two other available metrics and illustrates why Ph5 and PEI are indeed superior as they relate to pumps in specific. As well, the relationship between Ph5 and PEI is explained.

Specific energy and green pump index

When it comes to energy consumption, an often employed metric is the Specific Energy (or Volumetric Energy Consumption), measured in units of kWh/m^3 (or similar), basically expressing the amount of energy required to process a volumetric unit (i.e., 1 m^3) of water. While this may be a very useful metric for certain drinking water processes, such as treatment, it is incomplete when it comes to pumping. The reason for this is that it doesn't account for the entire productive output of the pump which includes both flow (volume) and TDH (lift). As a consequence, it can potentially yield misleading results. The impact is readily apparent in Figure 6 when reviewing a comparison of the results for both this metric and PEI for the Canadian test results (HydraTek 2013). The results are presented in relation to the tested efficiency loss, measured as the decrease in the tested peak efficiency relative to the manufacturer's best efficiency point. There is considerable scatter and no discernible trend in the data for the Specific Energy metric which, as one would expect, would increase as efficiency loss increases, as indicated in the PEI data. This is due to the Specific Energy not considering the pump's lift, a key output and determinant of energy requirements. It is clear that the PEI metric (and, by extension, Ph5) is superior for this purpose.

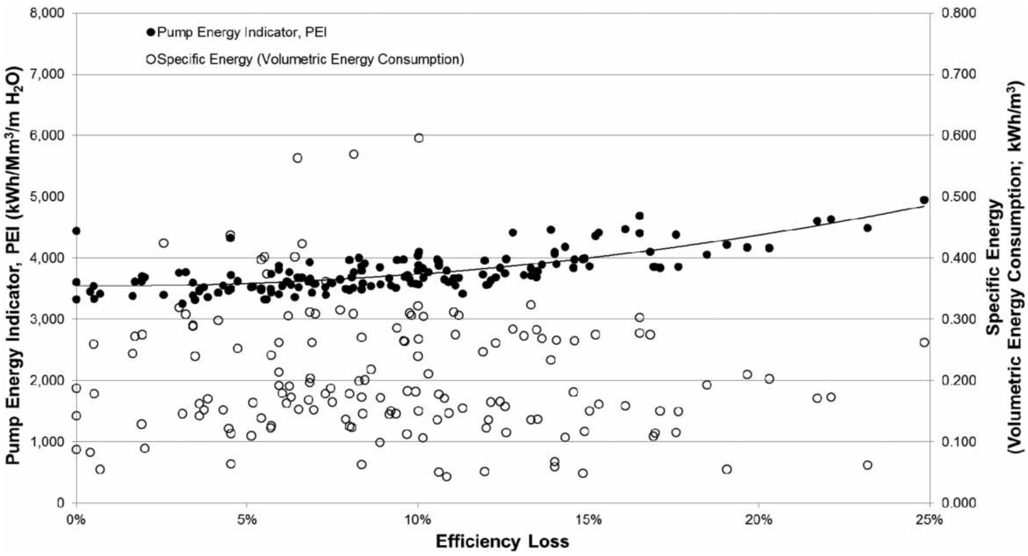

Figure 6 | Comparison of PEI and specific energy metrics for 152 pumps in Canada (HydraTek 2013).

The green pump index (GPX; Deritend & Riventa 2011) is a vast improvement over Specific Energy in that it explicitly considers the pump's lift, but does so in a somewhat incomplete manner. That is, it only considers the static lift of the pump which, arguably, is what the desired product of the pump is on a broader (e.g., system) level, however, it ignores the losses associated with friction losses which can be considerable. In many respects, the GPX is useful, particularly considering that the information requirements are less than that of the Ph5 or PEI. Comparing the results for these metrics from the Canadian experience (see Figure 7), the trends are comparable, although the degree of

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

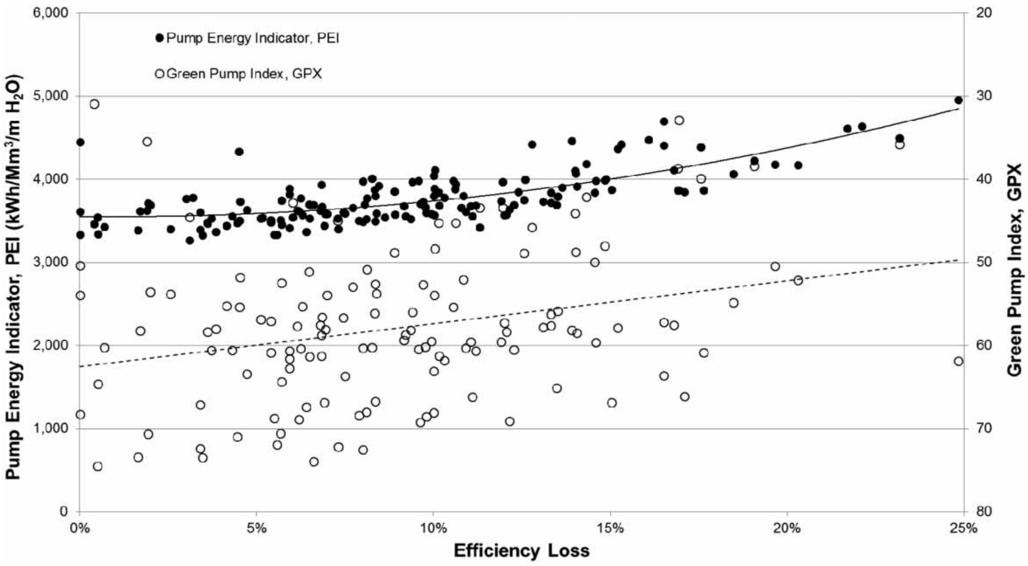

Figure 7 | Comparison of PEI and specific energy metrics for 152 pumps in Canada (HydraTek 2013).

scatter associated with the GPX is considerably higher, rendering the PEI (and, by extension, Ph5) superior to this metric also.

Relating PEI and Ph5

As noted above, the Standardised Energy Consumption (Ph5) performance indicator is closely related to the PEI, although there are some important, if perhaps subtle, differences. The most obvious differences are the reported units and timescale. The units are a matter of preference and do not detract from the concept. The timescale, on the other hand, does present some interesting differences.

Recall that the Ph5 is a long-term average, most commonly reported on an annual basis, whereas the PEI is an instantaneous measurement. Because Ph5 is an annual (or long-term) average, it does not explicitly consider the variation along the pump's operating curve which is itself valuable in understanding the pump's energy efficiency characteristics such that operating protocols can be adjusted to better suit the pump, or in determining whether the pump needs to be changed to better suit the system in which it operates (Papa *et al.* 2014).

Thus, the PEI is a more granular metric which, when factored with the duration of time the pump spends at each of its operating points over the course of a year, theoretically yields the Ph5 metric. This can be represented mathematically as:

$$Ph5 = \int f_Q(q) \cdot \mathrm{PEI}(q)\, dq \tag{4}$$

where $f_Q(q)$ is the frequency distribution of the pump flow (Q) and PEI(q) is the relationship between the pump's PEI value and pump flow. In reality, a continuous function as suggested in Equation (4) is not practical, although the concept remains valid and can be applied to the frequency of discrete flow intervals (i.e., histogram) that can be easily obtained through readily available data analysis tools (e.g., spreadsheets). This process is represented graphically in Figure 8.

Theoretical and practical imits of Ph5 & PEI

It is instructive to examine the limits of these performance indicators to understand their theoretical and practical ranges. Knowing this, erroneous or suspicious results can be identified and their input

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

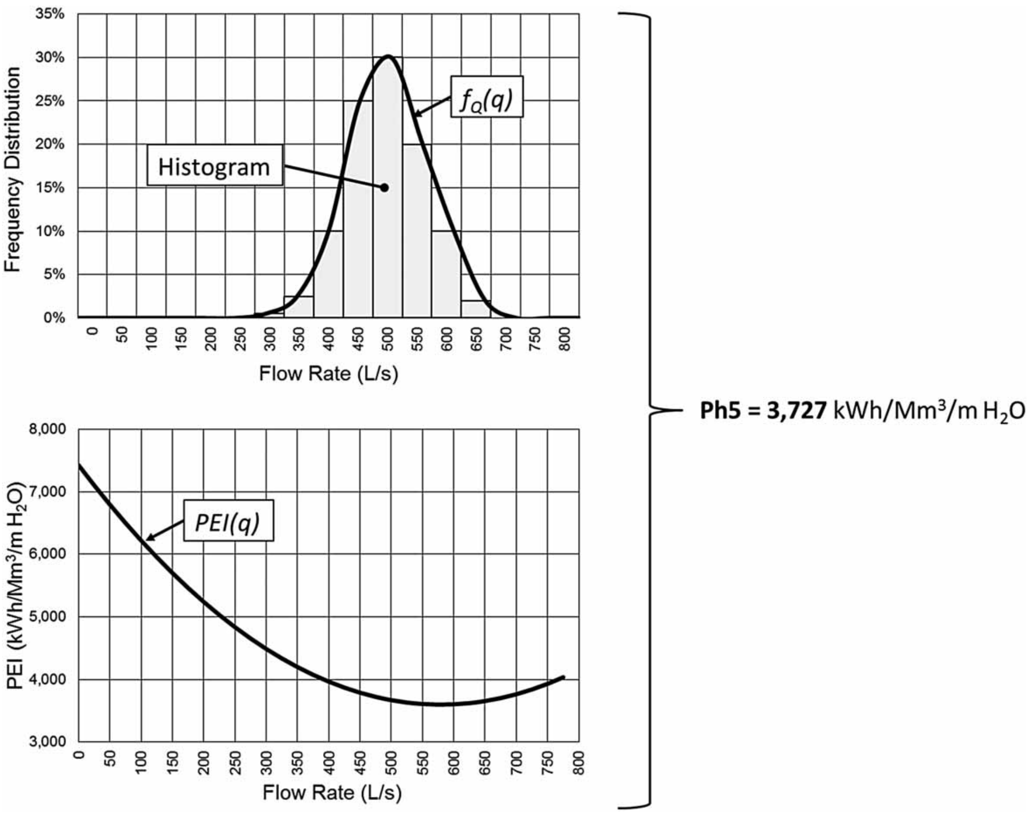

Figure 8 | Deriving Ph5 from PEI and frequency distribution of flow rate (operating point).

parameters scrutinized. As noted above, these metrics are based on the following calculation (subscripts removed):

$$Ph5(\text{orPEI}) = \frac{E}{V \cdot H} \tag{5}$$

Dividing both sides by time (t), we arrive at the following expression:

$$Ph5\ (\text{or PEI}) = \frac{\frac{E}{t}}{\frac{V}{t} \cdot H} = \frac{P}{Q \cdot H} \tag{6}$$

Rearranging Equation (1) we obtain:

$$\frac{P}{Q \cdot H} = \frac{\gamma}{\eta} = \frac{\gamma}{\eta_D \cdot \eta_M \cdot \eta_P} \tag{7}$$

Substituting Equation (7) into Equation (6) yields:

$$Ph5(\text{or PEI}) = \frac{\gamma}{\eta} = \frac{\gamma}{\eta_D \cdot \eta_M \cdot \eta_P} \tag{8}$$

This result has an interesting physical meaning in that the indicator is based on how efficiently the weight of the water is moved, which is (or ought to be) intuitive. Assuming no inefficiencies in the conversion of electrical power to water power (i.e., $\eta = 1$), we obtain the following theoretical

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

minimum value for these performance indicators:

$$Ph5_{\min} = \frac{\gamma}{\eta} = \frac{9,810\,\frac{\mathrm{N}}{\mathrm{m}^3}}{1.0} = 9,810\,\frac{\mathrm{N}}{\mathrm{m}^3} \times \frac{\mathrm{J}}{\mathrm{N}\cdot\mathrm{m}} \times \frac{\mathrm{W}}{\mathrm{J/s}} \times \frac{\mathrm{kW}}{1,000\mathrm{W}} \times \frac{\mathrm{h}}{3,600\mathrm{s}} \times 100 = 0.2725\,\frac{\mathrm{kWh}}{\mathrm{m}^3\cdot 100\mathrm{m}}$$

$$\mathrm{PEI}_{\min} = 9,810\,\frac{\mathrm{N}}{\mathrm{m}^3} \times \frac{\mathrm{J}}{\mathrm{N}\cdot\mathrm{m}} \times \frac{\mathrm{W}}{\mathrm{J/s}} \times \frac{\mathrm{kW}}{1,000\mathrm{W}} \times \frac{\mathrm{h}}{3,600\mathrm{s}} \times \frac{1,000,000\mathrm{m}^3}{\mathrm{Mm}^3} = 2{,}725\,\frac{\mathrm{kWh}}{\mathrm{Mm}^3\cdot\mathrm{m}}$$

Clearly, any pump operating measurements yielding values lower than the above minima are a physical impossibility and the quality of the measurements (or estimates thereof) should be scrutinized.

Of course, these pumping units contain inefficiencies and so it is useful to have an appreciation for what a practical lower limit of these performance indicators might be. To estimate this, we can ascribe the average value observed during the study in Canada (HydraTek, 2103) of 0.945 (or 94.5%) for the motor efficiency (η_M) and, since most pumps are not equipped with variable frequency drives, we can assume that the associated efficiency term (η_D) does not apply for this particular purpose. The pump efficiency (η_P) at the average of the manufacturer's best operating point (i.e., original pump condition) in the Canadian study was found to be 86.4%. Applying these values to Equation (8) and making the necessary unit conversions yields the following (rounded):

- Practical lower limit for Ph5 = 0.330 kWh/m^3/100 m
- Practical lower limit for PEI = 3,300 kWh/Mm^3/m

It is noted that this practical lower limit is not to be viewed as hard limit given the potential variability in the efficiencies used to calculate them, and whether or not additional elements (e.g., VFDs) are present in the system. The pump efficiency can be highly variable depending on the size of the pump and other factors and, in fact, the range of best efficiency points from original manufacturer pump curves in the Canadian study ranged from as high as 92.1% (for a 560 kW or 750 hp pump motor) to as low as 65.4% (for a 37 kW of 50 hp pump motor). More importantly, this calculation can be easily performed to suit the circumstances of any particular analysis.

In terms of a practical maximum, again the results from the Canadian pump testing program provides some guidance and a review of the most poorly performing pumps from that study suggest that a pump efficiency (η_P) of 0.50 or 50% would be a reasonable value to use for this purpose. Further, this value was obtained at the pump's typical operating point, rather than at the best operating point, and is considered to be more indicative when it comes to estimating the practical upper limit for this performance indicator. Applying this value to Equation (8), and assuming the lowest motor efficiency observed in the Canadian study (i.e., 89.5%) yields the following (rounded):

- Practical upper limit for Ph5 = 0.610 kWh/m^3/100 m
- Practical upper limit for PEI = 6,100 kWh/Mm^3/m

Similar to above, and for similar reasons, this should not be viewed as hard limit. Nevertheless, it does provide a guidepost that can be referenced when reviewing pump efficiencies in this light.

When applying these practical limits to the results from Mexico (see Figure 4), it is apparent that some of the reported results are outside of the lower limits i.e., physically impossible and, hence, the quality of data being used is questionable, thereby driving improvements in measurement, instrumentation, reporting and overall understanding. Through this process, it is expected that, over time, improvements in data quality and overall understanding will yield increasingly reliable results. In fact, the limits used to filter the results in the inaugural year of this initiative (2014) were considerably wider to tolerate inaccuracies in the data, and it is planned that this range will narrow in the current and future years as the overall states of awareness and practice improve, as intended.

Water Practice & Technology Vol 10 No 4
doi: 10.2166/wpt.2015.109

SUMMARY AND CONCLUSIONS

The need to understand pump performance and energy efficiency *in situ* is important for supporting energy conservation activities in utilities, particularly given the quantity of water pumped, as well as the height and distance (i.e., friction losses) and losses due to component inefficiencies it has to overcome, all of which determine the amount of energy required to deliver the desired level of service to users. Pump efficiency has been shown to degrade significantly and, in order to manage energy consumption (amongst many other important matters), it is important to measure and regularly monitor pump performance. Independently conceived and delivered initiatives in Mexico and Canada have taken steps to address the knowledge gaps and encourage the adoption of testing and measuring methods, and the determination of performance indicators which appropriately assess the efficiency with which pumps do their work. These initiatives can be viewed as belonging to a broader framework of continuous improvement, and significant progress has been made in a relatively short time, although much work remains to be done.

REFERENCES

Alegre, H., Baptista, J. M., Cabrera, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W. & Parena, R. 2006 *Performance Indicators for Water Supply Services*. 2nd edn. IWA Publishing, London, UK.

Cabrera Jr., E., Dane, P. & Haskins, S. 2011 *Benchmarking Water Services; Guiding Water Utilities to Excellence*. IWA publishing, London, UK.

Deritend Industries, Riventa Limited 2011 Green Pump Index: a methodology to benchmark in-situ pump performance. (Whitepaper).

Olivares, R., Cavaleiro de Ferreira, R., Alcocer-Yamanaka, V. & Hansen Rodrigues, P. 2015 Informe de la iniciativa CEEPA 2014: Resultados de conjunto – Benchmarking Perspectivas de mejora continua. ANEAS (Asociación Nacional de Empresas de Agua y Saneamiento de México A.C.) http://www.aneas.com.mx/contenido/InfBMCEEPA2014.pdf, visited 24 March 2015.

HydraTek, Associates. 2013 Toward Municipal Sector Conservation: A Pump Efficiency Assessment and Awareness Pilot Study. http://hydratek.com/opa, visited 24 March 2015.

Papa, F., Radulj, D., Karney, B. & Robertson, M. 2014 Pump energy efficiency field testing and benchmarking in Canada. *Journal of Water Supply: Research and Technology – AQUA*. *IWA Publishing* **63** (7), 570–577.