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Pump energy efficiency field testing and benchmarking in Canada

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ABSTRACT

A large-scale pump performance and efficiency testing program was conducted across the province of Ontario (Canada) involving testing more than 150 water pumps in eight municipal water supply and distribution systems. The program's objectives included raising awareness of the state of pump energy efficiencies and opportunities for energy conservation, as well as the development of a benchmarking report which can be used as a key reference by water utilities in their efforts to improve the energy efficiency of their pumping systems. This is the first program of its kind in Canada and seeks to establish an understanding of the performance and efficiency of water pumps in the field using state-of-the-art thermodynamic technology. The generalized results of this program indicate that the average efficiency of the pumps tested is 9.3% lower efficiency than the manufacturer's original claims at the best efficiency point, while the average gap between the manufacturer's original best efficiency point and actual point of operation in the field was 12.7%.
Key words | efficiency test, performance test, pump, thermodynamic method, wastewater, water

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INTRODUCTION

Pumping is a central component of municipal water supply and wastewater conveyance systems, and it consumes significant amounts of energy. Although pumps are typically selected and modelled based on manufacturer's tests, the reality is that pumps are often installed in non-ideal settings which may differ materially from those in the manufacturer's facilities. In addition, the expected performance deterioration over time gives rise to the potential use of inaccurate information. Consequently, the quality of planning and decision making may be adversely affected. Furthermore, the upward trend in electricity prices is motivating more critical assessment of energy efficiency.

Recognizing the critical link between water and energy, and the resulting synergies across the energy and water sectors, a large-scale province-wide pump testing program was initiated with the support of the Ontario Power Authority, an independent government-owned corporation responsible for, among other things, assessment of the long-term adequacy of electrical resources in the province, forecasting future demand and the potential for conservation. The program involved the following eight municipal water utility partners, selected to provide a representative cross-section of geography and size within the province: the Regional Municipalities of Durham, Halton, Peel, and Waterloo; the Cities of Hamilton and Ottawa; the Sault Ste. Marie Public Utilities Commission and the Windsor Utilities Commission.

This program represents an important cross-sector collaboration which promotes energy conservation and the resultant benefits of supporting efforts to reduce, defer or potentially avoid power supply system capacity expansions. Furthermore, it acts as a major catalyst to the municipal water utility industry to support energy conservation and achieve the financial benefits that accrue as a result of responsible asset management.

In total, 152 pump tests were conducted on water pumps ranging in size from 30 hp (22 kW) to 4,000 hp (3,000 kW) using the thermodynamic method. As part of the program, workshops were conducted with each of the participating municipal water utilities to discuss the

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fundamentals of pump operation, the energy consumption characteristics of pumps and the systems within which they operate, the testing methodology, and the results.

Thermodynamic method

The electrical power consumed by the motor of a constant speed pump is determined by the following equation:

$$P = \frac{\gamma \times Q \times H}{\eta_m \times \eta_D \times \eta_p} \quad (1)$$

where P is power consumed by pump, γ is specific weight of water, Q is flow rate, H is total dynamic head, η_m is motor efficiency, η_D is drive efficiency (where applicable), and η_p is pump efficiency.

There are two approaches available to measure the *in situ* performance and efficiency of pumps: the conventional and thermodynamic methods. Both directly measure the power input to the pump motor (P) and the pressure differential between the suction and discharge sides of the pump which, after accounting for elevation and velocity head corrections, determines the total dynamic head (H). Accurate measurements of these parameters are easily obtained using modern sensing equipment.

Also, for both the conventional and thermodynamic testing methods, the efficiency is determined by a combination of the motor, its drive (e.g., variable speed drive, if applicable), and the pump (i.e., $\eta_m \times \eta_D \times \eta_p$). In order to define pump efficiency, an estimate is required for both drive and motor efficiencies. These electric devices are designed and built to high standards with low error tolerances, and are not subject to physical degradation similar to pumps and other mechanical devices. As a result, the efficiencies of motors and drives vary little over time from their original state, and it is often sufficient to use manufacturer's information for different loads without compromising the determination of the pump efficiency.

Where the methods differ is in one of the remaining two variables in Equation (1), and the derivation of the other through computation. The conventional method requires the direct measurement of flow rate (Q) and solves Equation (1) for pump efficiency (i.e., η_p). Accordingly, the accuracy of estimating the efficiency is directly related to that of flow measurement. While several different technologies exist for measuring flow rates accurately, considerable effort is required to achieve stable flow conditions. In many existing pump installations, these conditions are often difficult to find, largely because they were designed and built without taking into consideration such factors as turbulence (thus necessitating sufficient lengths of straight run piping upstream and downstream of the meter), air, and/or vapour pockets, the presence of which can be exacerbated by pump cavitation, amongst other things which can significantly affect the accuracy of the flow measurement. Unlike in factory test conditions, it is quite challenging therefore to obtain accurate flow readings in existing field installations which do not feature the appropriate conditions to do so, thereby further compounding the inaccuracy of the pump efficiency measurement.

The thermodynamic method on the other hand relies on accurate temperature and pressure measurements of the fluid – water in this case – immediately upstream and downstream of the pump in order to quantify the thermal gain in the fluid. In the process of converting the mechanical energy of turning the pump into the combination of flow and pressure (total dynamic head) produced by the pump, any inefficiency in doing so is converted predominantly into thermal energy. Using thermodynamic relations, this thermal gain is used to determine the pump's efficiency and, if desired, the flow rate can be calculated using Equation (1). Consequently, by directly determining pump efficiency, the need to accurately measure flow, is avoided.

While the thermodynamic method does not rely on flow measurement, it does depend on the accuracy of temperature measurements. In fact, this approach was developed in the 1960s (UK Department of the Environment 1997), however, it has only recently grown in application as a result of the development of highly accurate and reliable temperature probes possessing long term stability. For this testing program, the P22^{TM} Thermodynamic Efficiency/Flow Meter developed by Robertson Technology (Australia) was employed. The temperature probes are capable of reliably measuring differential temperature with an uncertainty of less than 1 mK (10^{-3} °C) and long-term tests have shown that probe calibration is stable within a typical experimental error of <0.2 mK over a 5-year period (Robertson 2006). Each probe contains two temperature sensors and the software detects any discrepancies between the two, giving a warning if one starts to drift. The result is a reliable determination of pump efficiency and the subsequent and accurate derivation of flow rate. In fact, this methodology can also be used for the primary purpose of measuring flow in many applications.

Notwithstanding, it is important to note that this method is not applicable or as accurate in situations where the temperature probes cannot be installed to yield reliable results, or for pumps with very low heads. Experience in applying this method in wastewater systems has identified additional challenges relating to ragging of the temperature probes as well as their potential damage by large objects present in the flow stream (Radulj *et al.* 2012). Situations where there is insufficient mixing of separate flow streams of varying temperature immediately upstream of the pump can also give rise to suction temperature instability thereby affecting the quality of the results.

In order to ensure the success of pump testing program reported herein, a preliminary screening process was developed, applied, and refined. Given an initial set of candidate pumps suggested by each municipal utility, the results of the screening process narrowed the number of candidate pumps which were then subjected to field reconnaissance in order to identify the specific pumps to be tested and any preparation works required to do so. In many cases, new taps were required to enable the installation of the testing equipment. Additional references relating to the thermodynamic method include Cartright & Eaton (2009), Robertson & Rhodes (2008), Schofield (2007) and UK Department of the Environment (1998).

Testing procedure

The testing procedure covered as much of the operating range of the pumps as was practical or possible in order to compare the *in situ* characteristic curves of the pumps with the original ones of the manufacturer, as well as ensuring a proper understanding of the pump performance across its range. This also required making changes to the system where the pump operates.

Typically, the simplest and most effective way of imposing system changes is by progressively throttling the discharge valve of the pump, thereby increasing the resistance against which it is operating to higher head and a lower flow rate. Other methods for changing system conditions include operational modifications for parallel pumps both within the station and in the system, as well as for downstream pumps that draw from the same pressure zone. Consideration of reservoir and tank levels before and during the testing is often also required.

It is noted that the above testing procedure is mainly applicable to the generally high capacity and redundant systems typically found in Canada and the United States of America. The testing procedure to be applied in other systems needs to be tailored to their specific circumstances and it is acknowledged that it may not be practical or possible to test a wide range of operating points for systems in other jurisdictions or industries. Fortunately, the results of this program provide a useful reference for practitioners elsewhere seeking to understand how pump behaviour can vary outside of the ranges that they are able to test given the limitations in their systems.

In the case where pumping units included variable frequency drives (VFDs), these were set to run at a fixed rate – often at or near 100% – for the duration of the test, and the results were subsequently adjusted to the maximum speed using affinity laws.

TESTING RESULTS

Terminology

In order to quantify the loss of efficiency from the original manufacturer's condition of the pump to its tested *in situ* condition, two measures were identified: Efficiency Loss and Overall Efficiency Gap. Each of these is measured against the manufacturer's original best efficiency point (MBEP) which represents the maximum efficiency for the pump being tested. It is noted that the available literature on MBEPs is typically based on manufacturer generic test bench results and, as such, any inefficiencies between factory and *in situ* conditions upon original installation are included in the measures noted above.

The Efficiency Loss is the difference in efficiency (η) between the MBEP and the tested *in situ* best efficiency point (TBEP), all expressed in percentage terms. This provides an indication of the extent to which the pump's performance has deteriorated since its manufacture. Recovery of some or all of this reduced efficiency can be accomplished through pump refurbishments, for instance.

$$\text{Efficiency Loss} = \eta_{\text{MBEP}} - \eta_{\text{TBEP}} \quad (2)$$

The Overall Efficiency Gap is the difference in efficiency between the MBEP and the *in situ* efficiency of the pump at its typical operating point (TOP), all similarly expressed in percentage terms. This measure, in addition to taking into account the Efficiency Loss noted above, also accounts for any losses due to the pump operating outside of its peak efficiency point or range. Accordingly, recovery of some, if not all, of the reduced efficiency can, in addition to pump refurbishments, also be accomplished through changes in operation or replacing the pump with one that is better suited for the system in which it operates. In determining the typical (i.e., average) operating point, pump operation records, where available, or field observations during testing were used

$$\text{Overall Efficiency Gap} = \eta_{\text{MBEP}} - \eta_{\text{TOP}} \quad (3)$$

Sample results

Reports on each of the pump tests conducted included plots showing the performance characteristics of head (H), pump efficiency (η_p) and electrical power (P) across a range of flow rates. Typical results for one of the pumps are provided in Figures 1 and 2 which indicate that the *in situ* performance of the pump at the time of testing produced lower heads and efficiencies for a given flow rate (Figure 1), and accordingly consumed more power (Figure 2).

For this particular sample test conducted on a pump that was originally installed in 2007 (5 years old at time of test), the Efficiency Loss and Overall Efficiency Gap were calculated to be 8.3% (i.e., 81.7–73.4%) and 9.6% (i.e., 81.7–72.1%), respectively.

Additional useful information derived from the testing include: annual energy consumption based on typical pump utilization rate; estimates of annual cost savings from recovering some or all of the lost efficiency; estimates of annual greenhouse gas (GHG) emission savings from recovering some or all of the lost efficiency; pump power consumption energy metrics (see 'Benchmarking metrics' discussion below), etc.

Overall results

Testing was conducted for 152 pumps across the province of Ontario in 2011 and 2012. Of these, the majority (84%) were horizontal split case pumps. In terms of motors, 57% of the pumps tested were low voltage (600 V) and the remaining 43% were medium voltage (2,300–4,200 V). The average efficiency of the pumps at the MBEP was 86.4%.

The overall results found that the average TBEP was 77.2% and the tested TOP was 73.7%. Accordingly, the

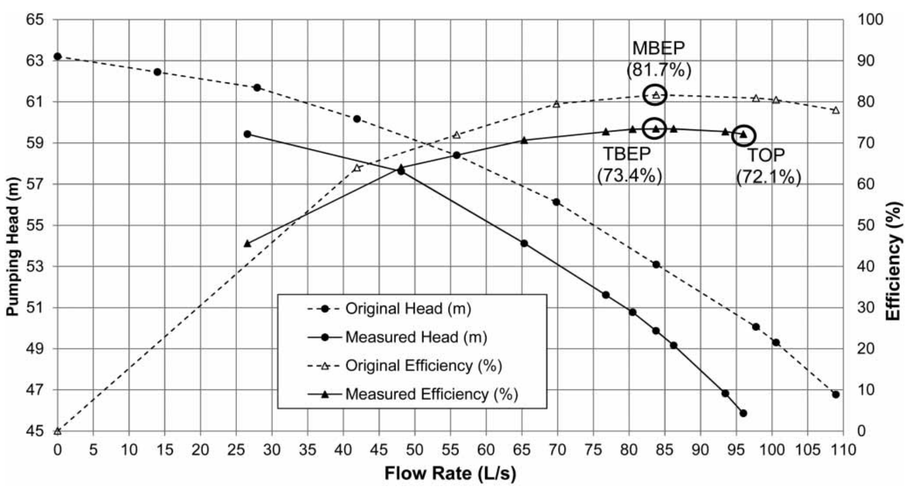

Figure 1 | Sample testing results for 100 hp (75 kW) pump: head and efficiency.

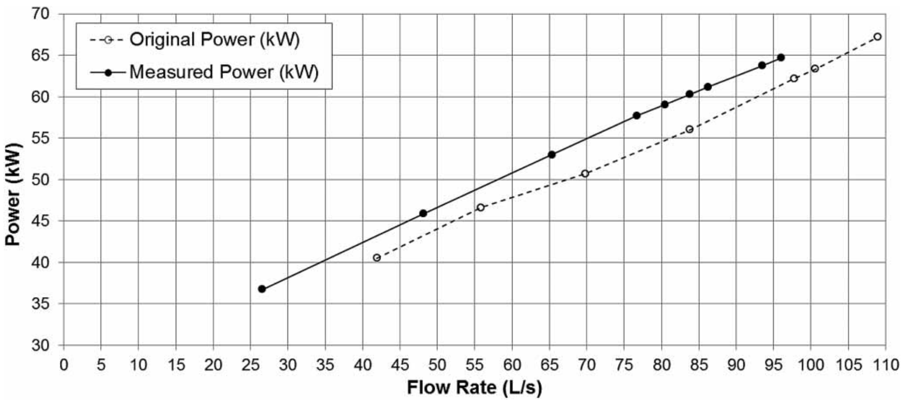

Figure 2 | Sample testing results for 100 hp (75 kW) pump: power consumption.

average Efficiency Loss of the pumps tested was 9.3% (i.e., 86.4–77.2%, subject to rounding error) while the average Overall Efficiency Gap was 12.7% (i.e., 86.4%–73.7%). Distributions of the results are provided in Figures 3 and 4.

Interestingly, while the ages of the pumps ranged from 1 year to 61 years with an average of 25 years, there was no discernable correlation between pump age and efficiency degradation. While potentially counter-intuitive, this was not entirely surprising given that the pumps in service undergo various forms of routine maintenance, repair, refurbishment and modification throughout their working life. In order to develop a better understanding of performance degradation, a deliberate testing program that controls these variables would be required and which was beyond the scope of the work reported herein.

The total annual power consumption for the pumps tested was determined to be greater than 160 MWh being equivalent to approximately 27,000 tonnes of GHG (based on 170 g CO_2/kWh; Environment Canada 2011) and costing approximately C$16 million. It is evident therefore that, given the above results regarding real efficiency rates, there is value to be captured through the improvement of pumping efficiency. Moreover, this value extends beyond

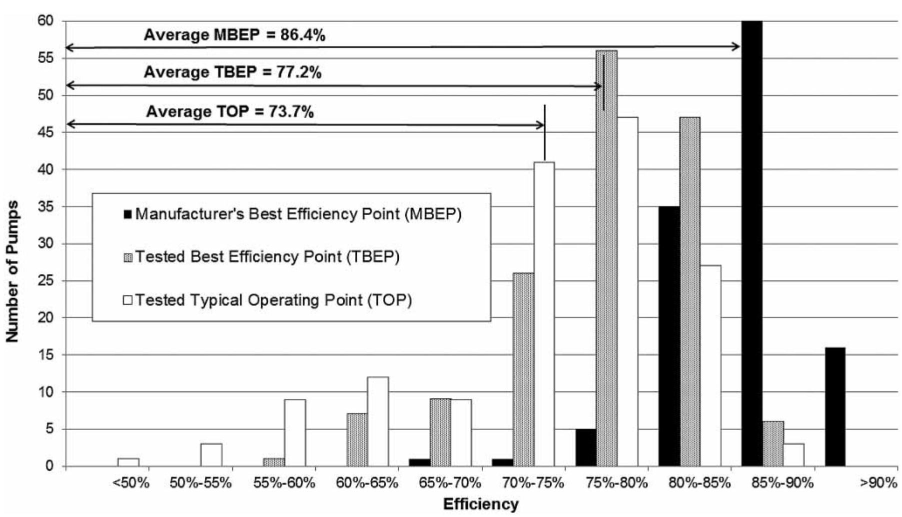

Figure 3 | Distribution of results for efficiencies at MBEP, TBEP and TOP.

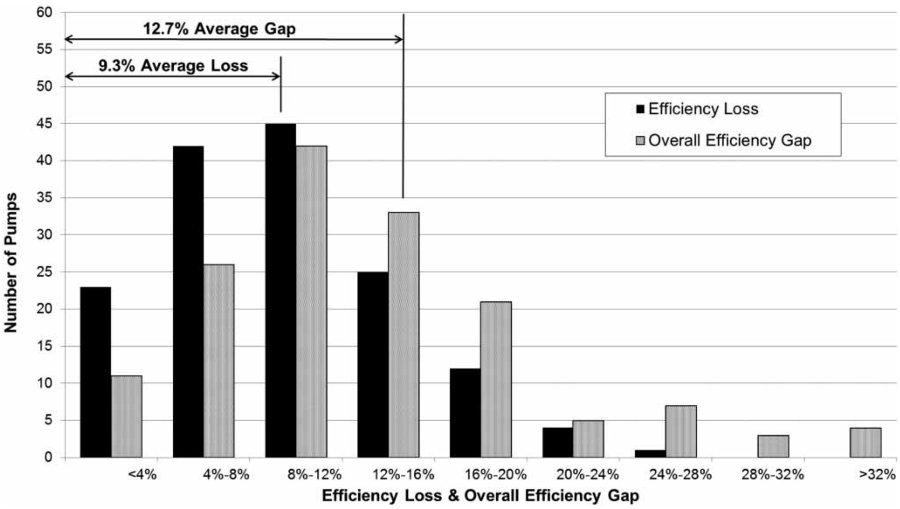

Figure 4 | Distribution of results for Efficiency Loss and Overall Efficiency Gap.

the pure financial business case relating to the cost of electricity, but to broader environmental objectives as well.

BENCHMARKING METRICS

Specific energy

An often employed metric to describe the power consumed by pumps is specific energy (often referred to as Volumetric Energy Consumption), and is the amount of power consumed per unit of volume pumped. Based on all the tests conducted, this metric was found to vary quite significantly both for the MBEP and TBEP, respectively, as indicated in Table 1. Despite the wide variation in results, it is evident that the *in situ* condition of the pumps consumed approximately 9.5% (i.e., 0.208 vs. 0.190 kWh/m^3) more power per unit volume at the best efficiency point.

Interestingly, the average specific energy at the tested TOP was found to be only 7.1% (i.e., 0.204 vs. 0.190 kWh/m^3) higher than the MBEP, and less than the increase noted for the TBEP. While this may appear to be counterintuitive at first glance, it is due to this metric only accounting for the volumetric displacement (flow) of the pump which, alone, is insufficient to characterize the pump's output which is actually a combination of flow and pressure (or head). While still a useful metric, it is incomplete in this context and a more holistic one is needed for reliable benchmarking purposes.

Table 1 | Specific energy (kWh/m^3)

	Average	Standard deviation	Coefficient of variation
MBEP	0.190	0.095	0.498
TBEP	0.208	0.102	0.490
Tested TOP	0.204	0.104	0.511

Pump energy indicator (PEI)

A new metric was developed during this program which expands upon the concept of specific energy and relates the power consumption more directly to the level of service provided by the pump. The PEI was developed which normalizes the specific energy metric against the head produced by the pump in order to provide a more consistent comparison for pumps of different pressure ranges.

Using this approach, the statistical analysis of the data yields a much narrower variation, illustrating that this metric more directly relates the power consumption to the desired output of the pump (i.e., both flow and pressure), and is accordingly more reliable for benchmarking purposes. Table 2 summarizes the findings from this study and the increase in power consumption per combined unit of flow and head at the best efficiency point from the manufactured

Table 2 | PEI (kWh/Mm^3/m H_2O)

	Average	Standard deviation	Coefficient of variation
MBEP	3,350	178	0.053
TBEP	3,770	317	0.084
TOP	3,980	526	0.132

state to the *in situ* state at the time of testing was found to be 12.5% (i.e., 3,770 vs. 3,350 kWh/Mm^3/m H_2O). At the TOP, the increase in energy consumption is a quite significant 18.8% (i.e., 3980 vs. 3,350 kWh/Mm^3/m H_2O).

The distribution of the results provided in Figure 5 can be a helpful reference for utilities when comparing results from individual pump tests. With this information, it is likely that recommendations can be made with respect to setting performance targets for pumps using this metric and which are under development at the time of writing. At the very least, it is easy to identify which pumps are performing poorly relative to this peer group and seek to improve them.

It is noted that the PEI metric closely resembles the Standardised Energy Consumption Performance Indicator (Ph5; Alegre *et al.* 2006; Cabrera *et al.* 2011). The main differences involve the units used, which is relatively minor, and the time frame for reporting. The Ph5 Performance Indicator is generally presented as an annual average while the PEI is based on instantaneous measurement and is capable of characterizing the pump's energy efficiency performance across its entire operating range which is quite variable. By considering the variation along the pump's entire operating curve, the PEI is useful in determining the impact of adjustments in operating protocols to better suit the pump, or in determining whether the pump needs to be changed to better suit the system in which it operates. That is, through the understanding of the PEI variability of a particular pump relative to the system it operates in, and adjusting the way the pump operates, the resulting Ph5 benchmarking metric which is measured at the end of a defined period of operation can be improved. Thus, the differences between PEI and Ph5, while apparently subtle, are not trivial and can be quite meaningful in their practical application. Of course, these differences can be easily reconciled with data on pump usage, factoring the duration of time the pump spends at each of its operating points over the course of 1 year. The results presented in Table 2 for Ph5 are as follows (assuming direct extrapolation to an annual average basis and assuming no variability in pump operating points over the duration of observation):

- MBEP: 0.336 kWh/m^3/100 m H_2O.
- TBEP: 0.377 kWh/m^3/100 m H_2O.
- TOP: 0.398 kWh/m^3/100 m H_2O.

These values compare favourably with those determined by others (ERSAR 2011).

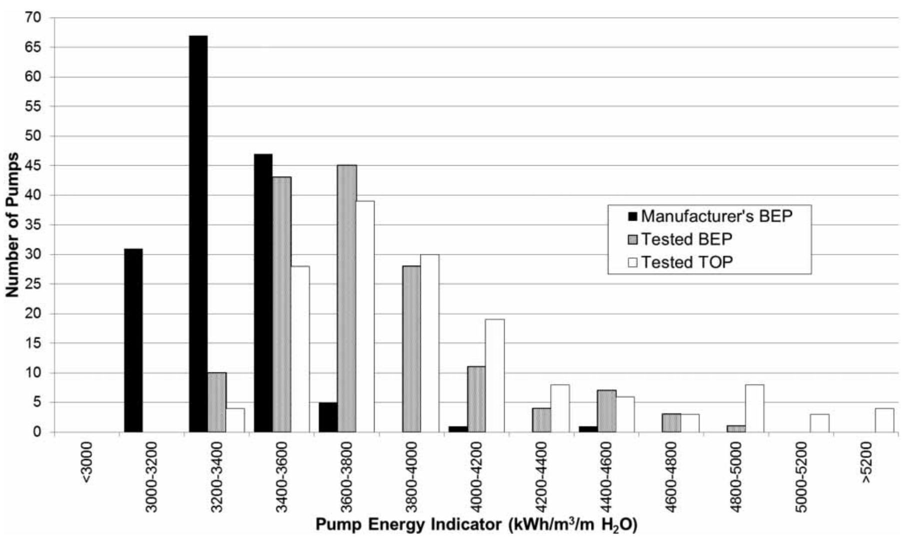

Figure 5 | Distribution of results for PEI.

CONCLUSIONS

Municipal water utilities have historically relied upon pump performance information relating to the new, manufactured conditions of pumps for use in the analysis and optimization of energy consumption. Moreover, very little attention has generally been paid in North America to understanding actual energy efficiency of pumps operating in the field, with consequently little awareness with respect to the magnitude and resulting cost of inefficiency. This is largely attributable to the very low historical electricity costs, although it is increasingly acknowledged that there is an upward trend in these prices in addition to broader scale fiscal pressures, thus motivating conservation and efficiency efforts.

This is perhaps the first large-scale testing program conducted which removes much of the speculation surrounding this matter and which clearly illustrates that current technology for *in situ* pump performance and efficiency testing, and the results that are derived therefrom, can provide the fundamental information, reliably and accurately, so as to support asset management as well as operational decision making. The PEI has been developed as a benchmarking metric (being a more granular version of the IWA's Standardised Energy Consumption Performance Indicator, Ph5) which can assist in identifying the amount of energy that a given pump consumes for delivering flow and pressure across its entire operating range in order to support changes to operating protocols or interventions such as pump or impeller replacements, as well as for making comparisons against original manufacturer information.

A significant number of pumps were tested and even though all pumps tested were located in a single jurisdiction (Ontario, Canada), the results may reasonably be extended to other locations within Canada and the United States of America, where operational and management practices are generally similar. It is acknowledged that even if these results may not be directly applicable to other jurisdictions; they represent an important step towards driving energy conservation and efficiency improvement across the entire municipal water utility industry.

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