Pump Energy Efficiency Field Testing & 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 more than 150 water pump tests in 8 municipal water supply and distribution systems. The program's objectives included raising awareness and 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 which seeks to broadly establish an understanding of the performance and efficiency of water pumps in the field using state-of-the-art technology and the thermodynamic method. The generalized results of this program indicate that the average pump tested had a 9.3% lower efficiency than the manufacturer's original claims at the best efficiency point (BEP); however, the average gap between the manufacturer's original BEP 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 installed in a variety of settings whose conditions may differ materially from those in the manufacturer's facilities. In addition, the expected performance deterioration over time also gives rise to the potential use of inaccurate information. Accordingly, the quality of planning and decision making may be adversely affected. Furthermore, the upward trend in electricity prices is motivating more critical assessment of the cost of energy consumption.

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 (OPA), 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 8 municipal water utility partners, selected to provide representative cross-sections of both geography within the province as well as municipality size: 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, on the one hand, promotes energy conservation and the resultant benefits of supporting efforts to reduce, defer or potentially avoid power production capacity expansions. On the other hand, this project continues to act as a major catalyst to the municipal water utility industry to support energy conservation and 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 4000 hp (3000 kW) using the thermodynamic method. As part of the program, workshops were conducted with each of the participating municipal water utilities which discussed the fundamentals of pump operation, the energy consumption characteristics of pumps and the systems within which they operate, the testing methodology, and the testing results.

Thermodynamic Method

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

$$P = \frac{\gamma \cdot Q \cdot H}{\eta_m \cdot \eta_p} \tag{1}$$

where,
P : power consumed by pump,
γ : specific weight of water,
Q : flow rate,
H : total dynamic head,
η_m : motor efficiency; and
η_p : pump efficiency.

There are two methods available to measure the *in situ* performance and efficiency of pumps: the conventional method; and the thermodynamic method. Both methods 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). Moreover, accurate measurements of these parameters are generally easily obtained using modern sensing equipment.

Also, for both the conventional and thermodynamic testing methods, the efficiency determined accounts for the combination of both the motor and the pump (i.e., $\eta_m \times \eta_p$). In order to isolate for pump efficiency, an estimate is required for motor efficiency. Given that motor efficiencies vary little over time from their original state, it is often sufficient to use manufacturer's information across different loads for this parameter without compromising the determination of the pump efficiency.

Where the methods differ is in the measurement of one of the remaining two variables in eq. 1, and the derivation of the other through computation. The conventional method requires the direct measurement of flow rate (Q) and solves eq. 1 for efficiency (i.e., η_p). Accordingly, the accuracy of estimating the efficiency is directly related to the accuracy of flow measurement and, while several technologies exist for measuring flow rates accurately, considerable effort is often required in order to produce acceptable flow conditions so as to generate accurate results. In many existing pump installations, these conditions are generally difficult to find, largely since they were designed and built without the need to accurately measure flow in mind. Matters that can significantly impair flow measurements include turbulence, thus necessitating sufficient lengths of straight run upstream and downstream of the meter, air, and/or vapour pockets, the presence of which can be exacerbated by pump cavitation, amongst other things. The point is that, and unlike in factory test conditions, it is quite often challenging 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 relies on accurate temperature and pressure measurements of the fluid – water in this case – immediately upstream and downstream of the pump in order to measure the heat gain in the fluid. In the process of converting the mechanical energy of turning the pump to the combination of flow and pressure (total dynamic head) produced by the pump, any inefficiency of doing so is converted into predominantly heat energy. Using thermodynamic relations, this heat gain is used to determine the pump's efficiency and, if desired, the flow rate can be calculated using eq. 1. By directly determining pump efficiency, the need to accurately measure flow as noted above, is avoided.

Of course, while this method does not rely on flow measurement, it does depend on the accuracy of temperature measurements. This method in fact was developed in the 1960s (UK Department of the Environment, 1997), however, it has only grown in application in recent times as a result of the development of highly accurate temperature probes with long term stability. For this program, the P22™ 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). Long-term tests have shown that probe calibration is typically stable within an experimental error of <0.2 mK over a five-year period. Each probe contains two temperature sensors and the software detects any discrepancies between the two sensors, giving a warning if one of the sensors 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 is also used for the primary and specific purpose of measuring flow in many applications.

Notwithstanding, it is important to note that this method is not applicable or as accurate in circumstances where the temperature probes cannot be installed so as to produce reliable results, or for pumps with very low heads. Experience with application of this method in wastewater applications has identified additional challenges related to ragging of the temperature probes as well as their potential damage as a result of possible large objects 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 give rise to suction temperature instability thereby affecting the quality of the results.

In order to ensure the success in testing of the pumps for the program reported herein, a preliminary screening process was developed, applied, and refined throughout the program. Given an initial set of candidate pumps offered by each of the municipal utilities, the results of the screening process narrowed the number of candidate pumps which were then subject to field reconnaissance in order to identify the specific pumps to be tested and any preparation work required in order to do so. In many cases, new taps were required in order allow for the testing equipment to be installed.

Additional resources 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 considered as much of the operating range of the pumps as was practical or possible in order to be able to compare the *in situ* characteristic curves of the pumps to the original manufacturer's curves, as well as to ensure a proper understanding of how each pump performs across its range. This required making changes to the system in which the pump operates.

Typically, the simplest and most effective way of imposing system changes is by throttling the discharge valve for the pump, thereby increasing the resistance against which the pump is operating and forcing it to move “left” on its curve to a new equilibrium point with a higher head and a lower flow rate than the previous point. Other methods for changing system conditions include operational decisions for parallel pumps both within the station as well as elsewhere in the system, as well as for pumps that draw from the pressure zone which is supplied by the pump being tested. Consideration of reservoir and tank levels before and during the testing is often required, as well.

It is noted that the above testing procedure is attainable for the generally high capacity and redundant systems typical of 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), the drives were set to run at a fixed rate – often at or near 100% – for the duration of the test, and the results were then subsequently adjusted to the maximum speed using affinity laws.

Testing Results

Terminology

In order to demonstrate 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 (BEP) which represents the maximum efficiency for the pump being tested.

The Efficiency Loss is the difference between the manufacturer’s original BEP and the tested *in situ* BEP. 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.

The Overall Efficiency Gap is the difference between the manufacturer’s original BEP and the *in situ* efficiency of the pump at its typical operating point (TOP). This measure, in addition to taking into account the Efficiency Loss noted above, also accounts for any efficiency losses due to the pump typically being operating outside of its peak efficiency point or range. Accordingly, recovery of some or 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.

Sample Results

Reports for 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 tested are provided in Figures 1 and 2; figures 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).

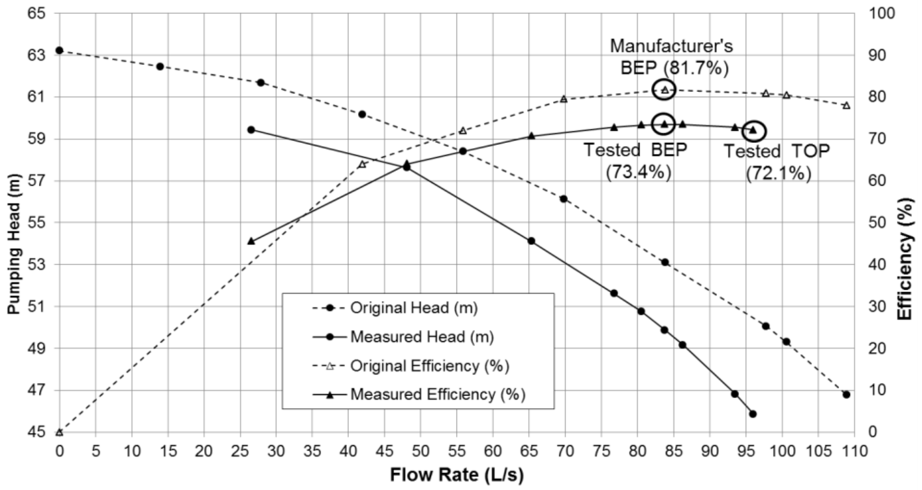

Figure 1 Sample testing results for 100 hp (75 kW) pump; head and efficiency.

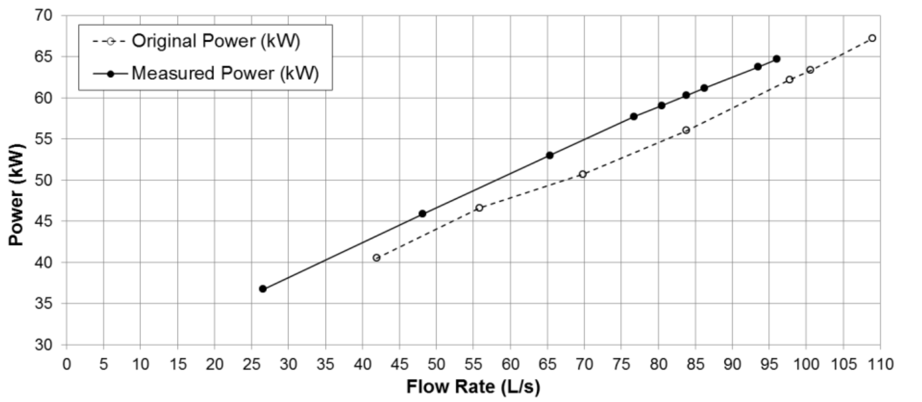

Figure 2 Sample testing results for 100 hp (75 kW) pump; power consumption.

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 are 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 (2300 V to 4200 V).

The overall results indicate that the average Efficiency Loss of the pumps tested was 9.3% while the average Overall Efficiency Gap was 12.7%. A distribution of the results is provided in Figure 3.

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. Therefore, it is evident 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 the pure financial business case in relation to the cost of electricity, but to broader environmental objectives as well.

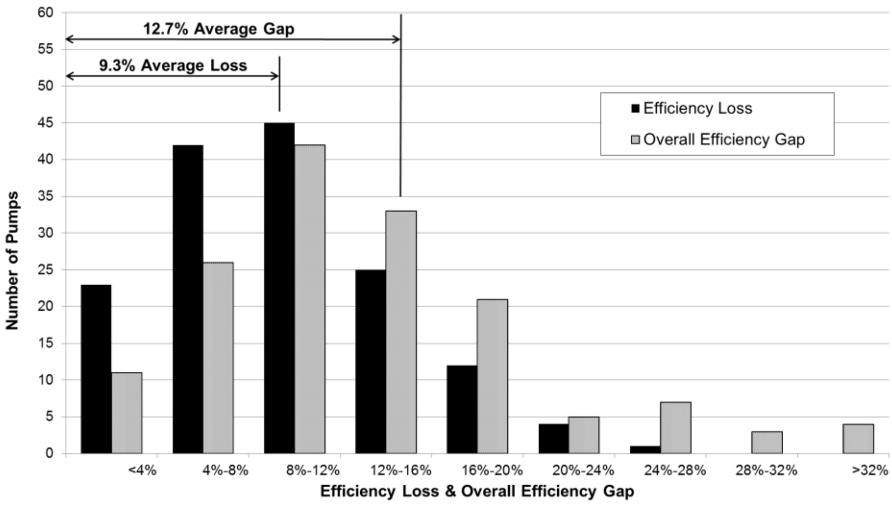

Figure 3 Distribution of results for Efficiency Loss and Overall Efficiency Gap.

Benchmarking Metrics

Specific Energy

An often employed metric which describes the power consumed by pumps is specific energy (or often referred to as Volumetric Energy Consumption), being the amount of power consumed per unit of volume pumped. Based on all the tests conducted, this metric was found to vary quite significantly for both the manufacturer's as well as tested best efficiency points, 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.

Table 1 Specific Energy (kWh/m^3).

	Average	Standard Deviation	Coefficient of Variation
Manufacturer BEP	0.190	0.095	0.498
Tested BEP	0.208	0.102	0.490
Tested TOP	0.204	0.104	0.511

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

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. That is, the purpose of a pump is to provide flow and pressure (head) and, in order to provide a more consistent comparison across pumps of different pressure ranges, the Pump Energy Indicator (PEI) was developed which normalizes the specific energy metric against the head produced by the pump.

Using this approach, the resulting statistical analysis of the data results in a much narrower variation than provided for by the specific energy, 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 quite reliable for benchmarking purposes. Table 2 provides 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 state to the *in situ* state at the time of testing was found to be 12.5% (i.e., 3770 vs. 3350 kWh/Mm^3/m H_2O). At the typical operating point, the increase in energy consumption is 18.8% (i.e., 3980 vs. 3350 kWh/Mm^3/m H_2O) which is quite significant.

Table 2 Pump Energy Indicator, PEI (kWh/Mm^3/m H_2O).

	Average	Standard Deviation	Coefficient of Variation
Manufacturer BEP	3350	178	0.053
Tested BEP	3770	317	0.084
Tested TOP	3980	526	0.132

A distribution of the results is provided in Figure 4 and which can be helpful for utilities to refer to when comparing results from individual pump tests conducted. With this information, it is reasonably foreseeable 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.

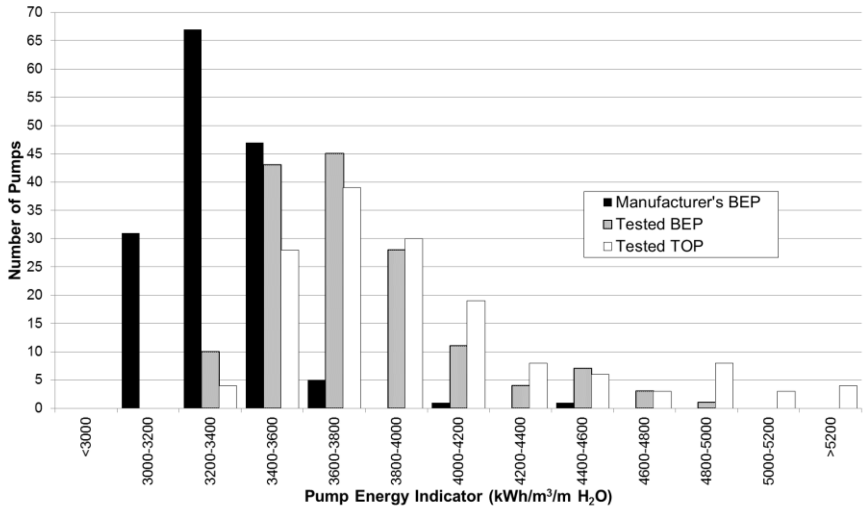

Figure 4 Distribution of results for Pump Energy Indicator (PEI).

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 accordingly little awareness with respect to the magnitude and resulting cost of inefficiency. This is largely attributable to the very low historical electricity prices, although it is increasingly acknowledged that there is an upward trend in these prices in addition to broader scale fiscal pressures, thereby 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 Pump Energy Indicator (PEI) has been developed as a benchmarking metric and which can assist in identifying the amount of energy that a given pump consumes for delivering flow and pressure, and for comparing that against original manufacturer information as well as the distribution of *in situ* testing results across the industry.

A significant number of pumps were tested and, although 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 these results may not be directly applicable to other jurisdictions; however, this represents an important step towards driving energy conservation and efficiency improvement across the entire municipal water utility industry.

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