PUMP PERFORMANCE & ENERGY EFFICIENCY TESTING & BENCHMARKING

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ABSTRACT

This paper provides an overview of pump testing methods, sample results, pump testing frequency guidelines and benchmarking metrics in addition to the application of pump testing for secondary flow meter verification all of which is derived from the authors' experience in practice.

Keywords: Pump Testing, Energy Efficiency, Thermodynamic Method

1 Introduction

The municipal water industry generally understands that pump efficiency is an important consideration for managing energy consumption given the associated operating costs. Further, the industry generally uses pump performance and efficiency curves to make design and operational decisions, noting that the curves used are commonly those supplied by manufacturers. All that said, however, the industry in general has a relatively poor understanding of the actual performance of individual pumps in practice, and the difference in a pump's characteristics between its original manufactured state and its actual operating characteristics can be meaningful and significant.

With the industry as a whole progressing and continually improving, pump testing is becoming more commonplace, yielding a wealth of information that extends beyond the pump itself, but also to the system it is operating in. This information is quite useful to system operators and asset managers in their activities to ensure reliable and affordable service. This paper provides a brief overview of pump testing methods and practical examples from the authors' experience to provide the reader with a glimpse of the valuable information that can be gleaned from pump testing.

2 Pump Testing Methods

There are two available methods for testing the instantaneous performance pumps: (i) the conventional method; and (ii) the thermodynamic method. (A third method, being the volumetric method, relies on the measurement of flow volume over a pumping cycle and, as such, can only provide average results over the pumping cycle, rather than instantaneous results at selected operating points. This method is more commonly applied in wastewater systems, although it may be used in water systems as well.) The instantaneous (i.e., conventional and thermodynamic) methods are the focus of this paper and are briefly discussed in this section, however, in advance thereof, it is worthwhile briefly describing the governing equation relating to the transformation of electrical power to water power (i.e., the desired output of the pump):

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

where P is the electrical power input to the pumping unit (herein defined to include the pump drive, pump motor and pump itself), γ is the unit weight of water, Q is the flow rate, H is the head (or pressure) delivered by the pump, η_D is the efficiency of the pump's drive (i.e., in the case of a variable frequency, or variable speed, drive) in adjusting or moderating the characteristics of the incoming electrical power for the pump motor, η_M is the efficiency of the pump's motor at converting the incoming electrical power to mechanical (rotational) energy, and η_P is the efficiency of the pump at converting the incoming mechanical energy to water power (being the product of γ, Q and H). Together, the product of the three efficiency terms is the overall efficiency of the pumping unit and is commonly referred to as the wire-to-water efficiency.

For the purpose of this paper, the terms η_D and η_M are given very little attention and, in most practical situations, are assumed as constants at or near their manufacturer's specifications. The underlying rationale is that these terms are generally quite high and tend to vary little over time in comparison with the generally significantly lower magnitude and wider variability of pump efficiency (η_P); therefore, measurements of these values (i.e., η_D and η_M) are less meaningful for the task at hand. As well, the unit weight of water (γ) is a property of water and need not be measured. The remaining parameters (i.e., P, Q, H and η_P) are what remain to solve the equation.

Of these parameters, the measurement of power (P) and head or pressure (H) are relatively straightforward and common for both testing methods. Power parameter (e.g., voltage, amperage and phase angle) readings can be measured directly and accurately at the power supply to the pumping units with the appropriate equipment which is commonly available. Head or pressure readings are similarly taken directly and accurately using pressure transducers placed immediately upstream and downstream of the pump, accounting for elevation and velocity head differences as well as local (non-pump) friction losses between these points.

Where the methods differ is as follows:

- For the conventional method, flow (Q) is measured and pump efficiency (η_P) is subsequently derived, making it an indirect measurement of efficiency which is heavily reliant on the quality of the flow measurement; and
- For the thermodynamic method, the temperature gain across the pump is measured using temperature probes with a high level of precision (±0.001 K or ºC) and, coupled with the heat capacity amongst other properties of water, the pump efficiency (η_P) can be directly and reliably calculated, and the flow rate (Q) can then be derived indirectly. This method, relying on the law of conservation of energy, recognizes that any input energy which is not converted to productive work is essentially converted into thermal energy.

While there are several advantages and disadvantages in relation to application of each of these methods, perhaps the most distinct advantage of the thermodynamic method is that it does not rely on a direct measurement of flow. Accurate flow measurements are often difficult to achieve in the field and are dependent upon various matters, including hydrodynamic characteristics of flow at the point of measurement as well as the consistency of the fluid (e.g., presence of air or vapour pockets), which can vary over time with flow rate and pump combinations, for example. The reality of most pump installation is that they are fit into rather tight quarters with numerous bends and other fittings in near proximity such that flow is rarely behaved well enough for accurate flow measurement, particularly at the individual pump level. This issue is often less of a concern on header or manifold pipes, but these elements too may also exhibit undesirable flow characteristics from the perspective of flow measurement. Additional discussion on this issue is provided in a later section of this paper.

In the authors' experience with testing over 300 pumps in Canada, the United States of America and Mexico, including a study of 152 water pumps across Ontario, Canada [1], it has been found that the thermodynamic method is more often applicable for accurate results. That said, the method does not work in certain applications, and both methods have been shown to provide reliable results under favourable conditions. The selection of which method to apply for any particular pump relies on judgement supported by a review of drawings and reports related to a facility's design and, quite importantly, advance field reconnaissance. Notwithstanding, there are certain indicators and guidelines which can be used in a general sense to screen for testing methods, however, a proper and thorough discussion is well beyond the scope of this paper.

3 Pump Testing Results

In general, the field testing of pumps has proven that there can be quite a bit of deviation between actual pump performance and that of its original manufactured condition. These deviations are often manifested in a reduced amount of head (or pressure) produced at a given flow rate, a reduced efficiency at a given flow rate, and an increase amount of power consumption at a given flow rate. Sample results from the Ontario study [1] are provided in Figure 1 for illustration.

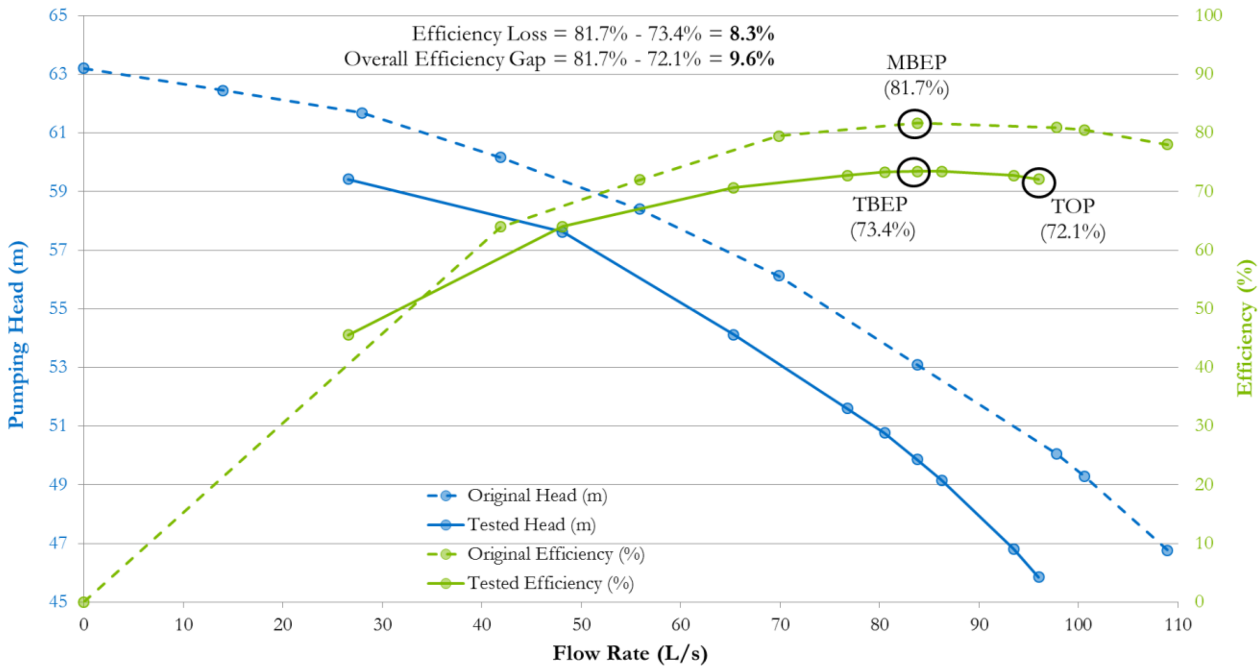

Figure 1. Example of Actual Pump Performance Characteristics as Measured in the Field Compared to Original Manufactured Condition [1]

The Ontario study [1] involved potable water pumps with motor sizes ranging from 30 hp (22.5 kW) to 4,000 hp (3,000 kW), and produced the following average results:

- The average pump efficiency of all the pumps tested, at their typical operating point, was found to be 73.7%;
- The average wire-to-water efficiency of all of the pumps tested, at their typical operating point, was found to be 69.4%;
- The average efficiency loss, being the difference between the best efficiency points on the original manufacturer pump curve and the field tested pump curve, was found to be 9.3% (in absolute terms); and

- The overall efficiency gap, measured as the difference between the manufactured best efficiency point and the efficiency at the typical operating point for the pump in the field, was found to be 12.7% (in absolute terms).

These average results, as well as specific results for individual pumps, have been used to formulate business cases for initiatives to improve energy efficiency (and reduce energy consumption). Such improvements commonly include pump refurbishments whereby the efficiency of the pump is restored, or changes in pump operating protocols whereby the pump is scheduled to operate more frequently in a region of higher efficiency based on its field-tested curve. The former method can involve considerable expenditure, while that for the latter is more modest and involves mostly analytical and logic control programming work.

Quite notably, the Ontario study [1] included the testing of two pumps pre- and post-refurbishment with comparable results whereby 65% to 71% of the efficiency loss (as defined above) was recovered. Similar tests conducted by the authors following conclusion of that work yielded similar results. Consequently, this information is useful in further strengthening business cases and, in fact, several Ontario utilities have successfully been awarded incentives in recognition of reduced power consumption as a result of such initiatives.

As well, in recognition of the principal drivers of pump energy consumption, being power consumed and run time (or utilization rate), an economic model was developed in that work which was in turn used to provide guidance on pump testing frequencies. The results of this are presented in Figure 2, relating recommended testing frequencies to pump motor size (in terms of horsepower) and the annual utilization rate of the pump.

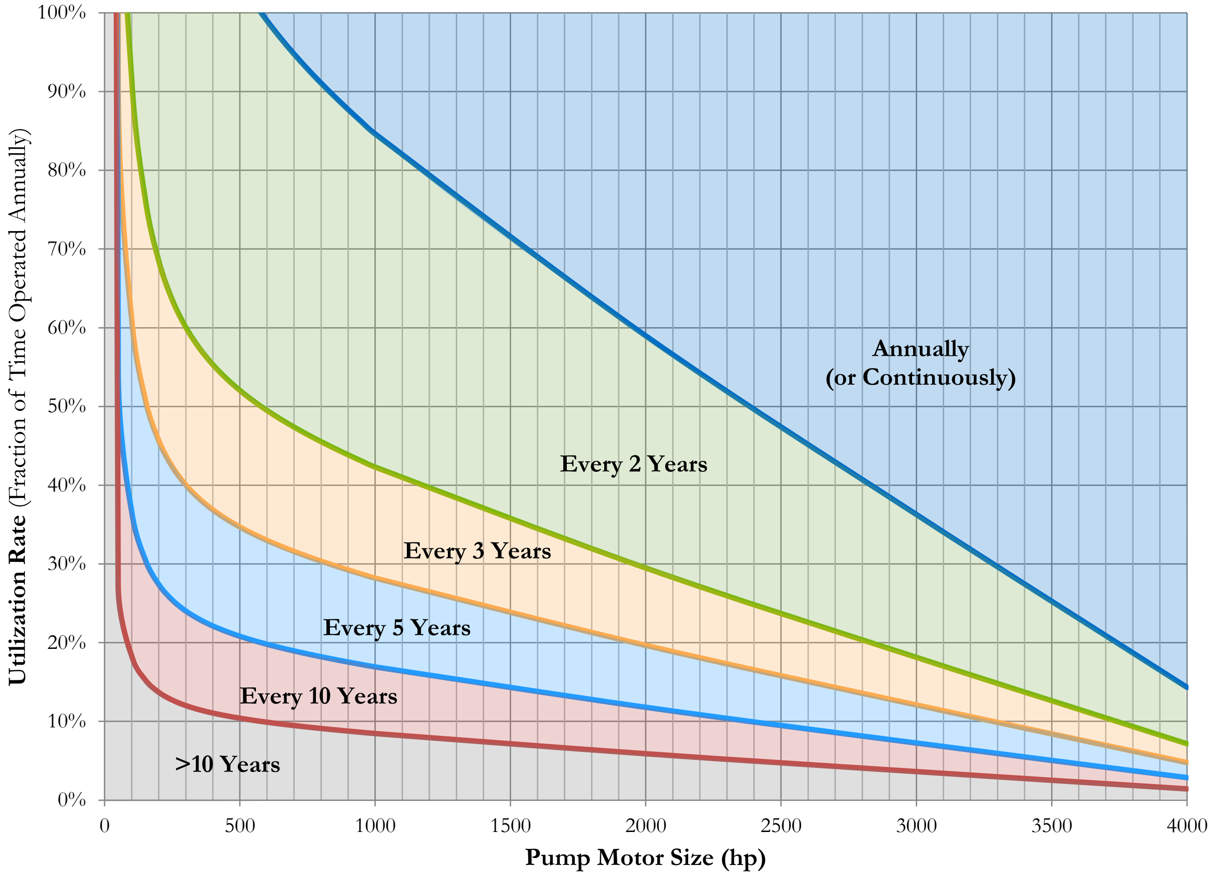

Figure 2. Guideline for Pump Testing Frequency [1]

The reader is encouraged to consult the publicly available report which outlines the development methodology and assumptions underlying this guideline, including the cost of energy applied, in order to determine whether the guideline is suitable for a particular utility given its unique circumstances. Nevertheless, such a tool is expected to be useful for planning activities to support operational and asset management strategies. Further, it is important to note that the guideline is based solely on financial matters related to energy consumption and refurbishment costs, and does not explicitly consider how critical a pump may be to any particular operation. It is logical and sensible that critical pumps be tested with a higher frequency than less-than-critical pumps, all else being equal.

4 Benchmarking

Any benchmarking exercise involves the development and use of performance indicators (PIs) that are reliable at, as the name implies, providing an indication of the performance of some activity or process and that can be measured relatively easily and repeatedly. When considering the function of pumps alone, their function is to convert electrical power to water power which, in turn, is the product of the unit weight of water (γ), flow (Q) and head or pressure (H), it is logical to normalize power consumption against both these parameters.

There are two parameters used in the industry for this purpose:

- The Standardized Energy Consumption (IWA performance indicator Ph5) [2,3] which is calculated using the energy consumption of a particular pump over a specified time period (typically long durations ranging up to one year), the volume of water processed by the pump over the same period, and the head delivered by the pump. Accordingly, this is an average indicator for the period in question.
- The Pump Energy Indicator (PEI) which was developed as part of the Ontario study [1] is similar in concept, however, is an instantaneous measurement of energy consumption per unit of flow rate and unit of head. As such, the entire flow range of the pump can be characterized and provides more specific information that can be used to guide improvement measures, particularly those related to changes in operating protocols.

Both of the above indicators are related to each other and the former can be mathematically derived from the latter, however, each has its independent merits depending on what information is sought or useful to the analyst. A more thorough description of these PIs and their interrelationship is available in the literature [4], as is the demonstration of their superiority to other indicators for this particular purpose [1,4].

In a practical sense, these indicators provide an indication of cost in terms of energy needed (e.g., kWh) to produce a desired output (i.e., Q and H) and, in essence, are an inverted version of the efficiency curve. The method of presentation, however, tends to carry a more direct meaning that can be used for conceptualization as well as calculation.

Assuming no inefficiencies in the pumping unit, the theoretical minimum for both of these parameters is 0.273 kWh/m^3/100m (or 2,730 kWh/Mm^3/m). A practical lower limit of 0.330 kWh/m^3/100m (or 3,330 kWh/Mm^3/m) and a practical upper limit of 0.610 kWh/m^3/100m (or 6,100 kWh/Mm^3/m) have been suggested based on available testing results [4]. Of course, these limits are useful for pumps similar to those used in the field pump tests from which they were derived, being the Ontario study [1] which found the average typical operating point to be approximately 4,000 kWh/Mm^3/m.

5 Pump System Energy Optimization Example

The PEI indicator has been applied to provide guidance towards optimizing individual pumping stations as well as to several pumping stations operating in a common pressure district (or zone) of a water distribution system. Ideally using results from in situ pump and system curve tests, PEI curves can be derived for pumps acting individually and in combination with other pumps. Figure 3 presents an example of a pumping station with 6 pumps and 14 possible pump combinations for which the PEI curves have been derived (broken coloured curves). By plotting the pump characteristic (i.e., head vs. flow) curves and identifying where they intersect the system curve range (black curves), pump combinations which utilize the least amount of energy to deliver the necessary flow can be identified, as indicated. The logic controlling the pumps in the station can then be tailored to select the most efficient pump combinations to deliver the service needed and based on the conditions at the station.

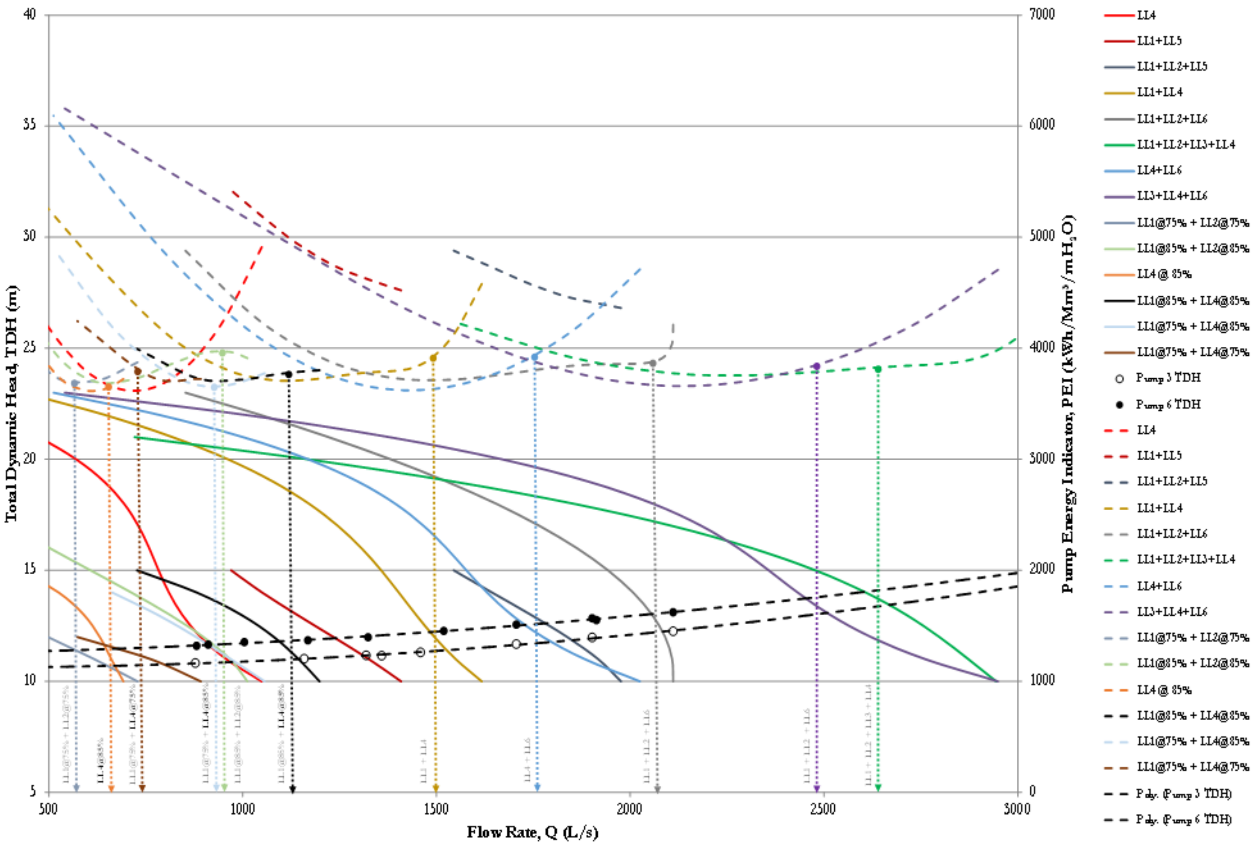

Figure 3. Using the Pump Energy Indicator (PEI) Metric to Optimize Pump Selection

6 Flow Meter Verification

One of the perhaps less obvious applications of the thermodynamic pump testing method is its ability to measure pump flow rates indirectly and which can be used for secondary verification of flow meters. Drawing from the authors' project experience, some examples of this application are presented below. The project locations and specific details are kept anonymous in the examples to respect the confidentiality arrangements in place, however, the examples are intended to provide sufficient insight to the reader to adequately demonstrate the principles discussed.

In one example, illustrated in Figure 4, the flow rates measured using the thermodynamic method at four individual pumps (labelled "P1" to "P4") are compared against the pumping station's flow meter (labelled "SCADA") situated on the facility's discharge header. In this particular case, it can be seen that there is excellent agreement between the measurements, giving comfort to the utility with respect to the accuracy of the station's flow meter.

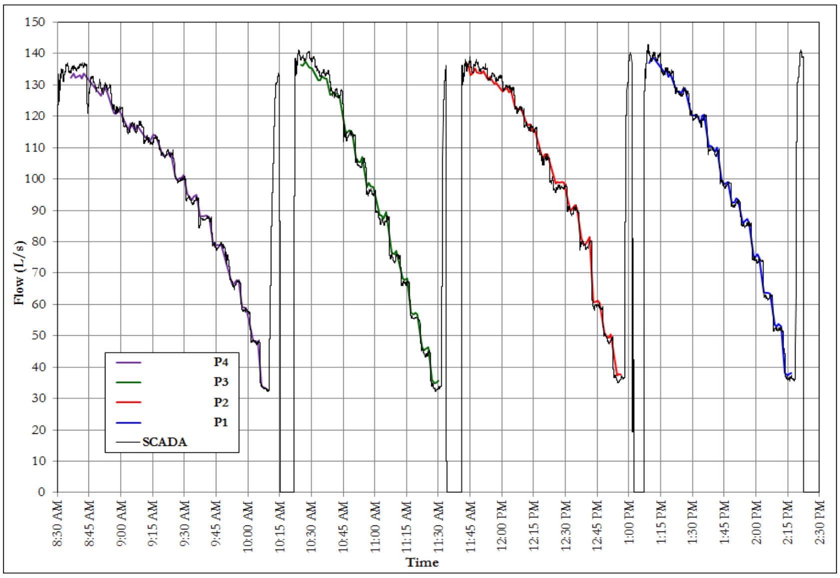

Figure 4. Example of a Favourable Comparison between Flow Rates using the Thermodynamic Pump Testing Method and Pump Station Flow Meter

Such favourable results, however, are not always found in practice. The example illustrated in Figure 5, similarly showing flow rates measured using the thermodynamic method at three individual pumps (labelled "P1" to "P3") are compared against the pumping station's flow meter (labelled "SCADA") and whose results show a significant discrepancy between the measurements. In this particular case, the pump station's flow meter over-estimated flow rates to varying degrees and caused the utility's calculations for non-revenue water (NRW) and, in turn, estimated real water loss (i.e., leakage), to be artificially high. In response to this, the utility deployed substantial resources to detect major leaks in its system to no avail. Upon receiving the results of the comparison shown, the estimated NRW fell in line with the utility's expectations and the station flow meter measurement error was subsequently rectified.

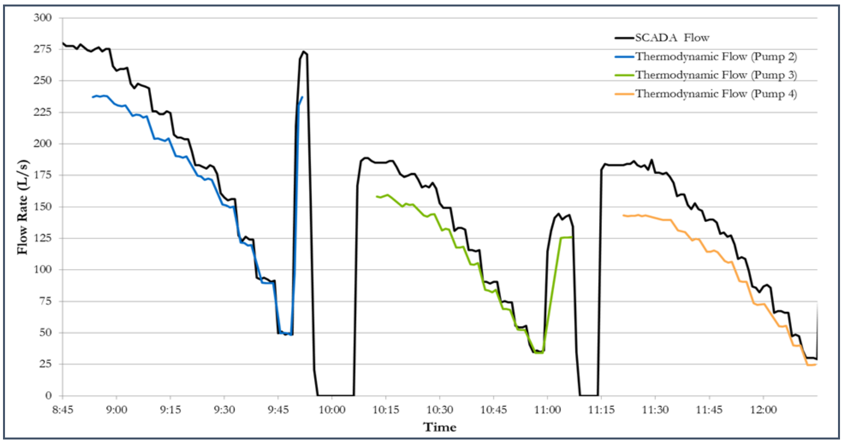

Figure 5. Example of Pump Station Flow Meter Inaccuracy as identified using the Thermodynamic Pump Testing Method

Inaccuracies of this kind are not uncommon, and are often the result of hydrodynamic conditions in the flow which compromise the ability of the flow meter in question to measure accurately. This may include flow turbulence, air or vapour entrainment in the flow at the pumps, swirling flow, amongst other matters.

Similarly drawing from the author's project experience, a major billing meter was found to be measuring inaccurately which gave rise to a payment concerns (disputes). It was found that the hydrodynamics of the flow in the discharge header, where a pressure differential type flow meter was situated, that was fed by several pumps which could be operated in numerous combinations, was one of the major contributors of the inaccuracy. To help resolve matters, the authors undertook a computational fluid dynamics (CFD) exercise to understand the then existing hydrodynamic conditions and subsequently support the design of a retrofit which employed, amongst other things, a flow straightener upstream of a new flow meter based on an alternative technology. The images presented in Figure 6 illustrate three of the iterations in the re-design process where the flow regime is progressively improved based on the features and configurations employed.

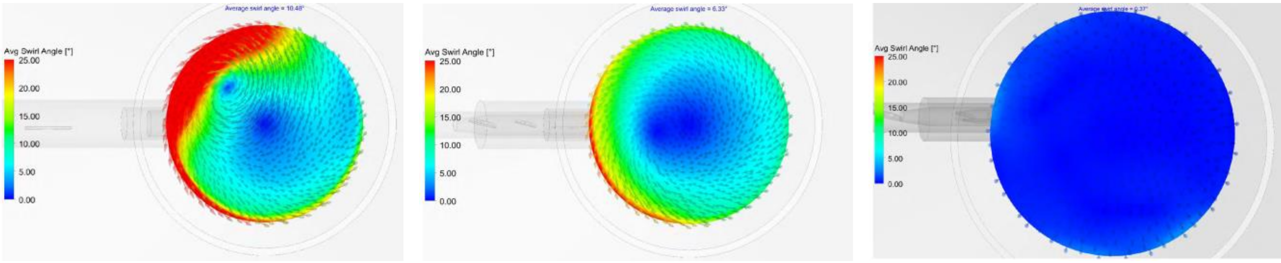

Figure 6. CFD Modelling of Hydrodynamic Flow Regime at Flow Meter Location for Progressive Re-Design Iterations

7 Conclusion

The successful and efficient operation of water distribution systems, as well as the planning and implementation of successful system interventions, demand a proper and accurate understanding of the characteristics of its components, importantly including pumps. The application of pump testing to provide the necessary information to system analysts, operators and planners is increasing in its adoption throughout the industry, and valuable information and insights that extend beyond the characteristics of the pump itself can be gleaned from such work. Pump testing, as such, is a logically integral part of operational and asset management activities for water utilities.

Of the two testing methods available, the thermodynamic method has been found to be generally (but not universally) more applicable and reliable at obtaining accurate results which, in large part, is attributed to its lack of reliance on accurate flow measurement. The determination of which method to apply is properly conducted through a review of facility drawings, design reports and field reconnaissance in advance of the testing.

8 References

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