Efficient Operation of Centrifugal Pumps

Troy Leyden

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Troy Leyden[1]

[1]Variable Efficiency, Gracemere QLD 4702, Australia
lncs@springer.com

Abstract. This paper aims to present maintenance cost and energy consumption, the major Life Cycle Costs (LCC) of a pumping asset, in a manner that can be appreciated by non-technical project stakeholders. The efficient operation of a centrifugal pump extends beyond reducing the energy consumed. As demonstrated by Barringer, efficiency and reliability are related. That is, the pump operation point relative to the Best Efficiency Point (BEP) affects the Mean Time Between Failure (MTBF) significantly. To demonstrate the LCC implications of design decisions, the expected rate of component wear will be evaluated using a technique that considers pump and systems specific parameters to give a cost per unit volume pumped for various flow rates. This will then be combined with the expected specific energy and presented in a table for the system being analyzed. The results shown clearly identify that the minimum combined expense does not necessarily correlate with either the minimum specific energy or maximum pump efficiency. Additionally, a graph that is representative for the entire operating range of a variable speed driven centrifugal pump is presented. The graph has the ability to allow various operational scenarios and system designs to be reviewed in a financial context by non-technical project stakeholders. Finally, an example of the increased energy consumption that might occur due to expected operational wear will be presented. This acts a demonstration of the proportion of energy lost to component wear, the effect this has on the system efficiency, and the value of operational monitoring systems.

Keywords: Energy efficiency, Material efficiency, Centrifugal pump, Life cycle cost, Rate of wear, Energy cost of wear.

1 Introduction

The focus of this paper is to highlight the importance of considering the Life Cycle Cost (LCC) when making design decisions. For example, the number of pumps required to deliver the nominated duty, and the anticipated range of operation for each pump, will ultimately determine the expected rate of wear and energy consumed.

Quantifying the rate of wear in a similar metric as specific energy (Es), that is, cost of refurbishment per megaliter pumped ($/ML), in conjunction with allocating an energy cost, allows both expenses to be combined and trended as a single metric across the range of Flow (Q) and Head (H) on a pump characteristic curve. This methodology and associated graphical representation allow insight for operational decisions for the two biggest Costs in the Life Cycle of a pumping asset.

While these expenses are well known, a graphical representation across the entire operation range is uncommon. This graph has been successfully used to communicate technical findings to non-technical stakeholders' numerous times and has been very well received.

2 Background

Cost is typically a paramount consideration when reviewing pump station design options. It is well established that the initial capital cost is a minor expense relative to the cost of energy and maintenance, which cumulatively form the major expense. The ability to identify the effect design decisions will have on the major expense over the life of the project enables those future costs to be assessed at the design phase.

Pump stations often operate well below the nominated duty they were designed to achieve. Figure 1 demonstrates the percentage of run time verse the proportion of nominated flow rate for three pump stations. The data displayed was collected over the period of a year and demonstrates that each pump station shared a common characteristic, it was operated at less than 50% of the nominated duty for more than 50% of the time it operated.

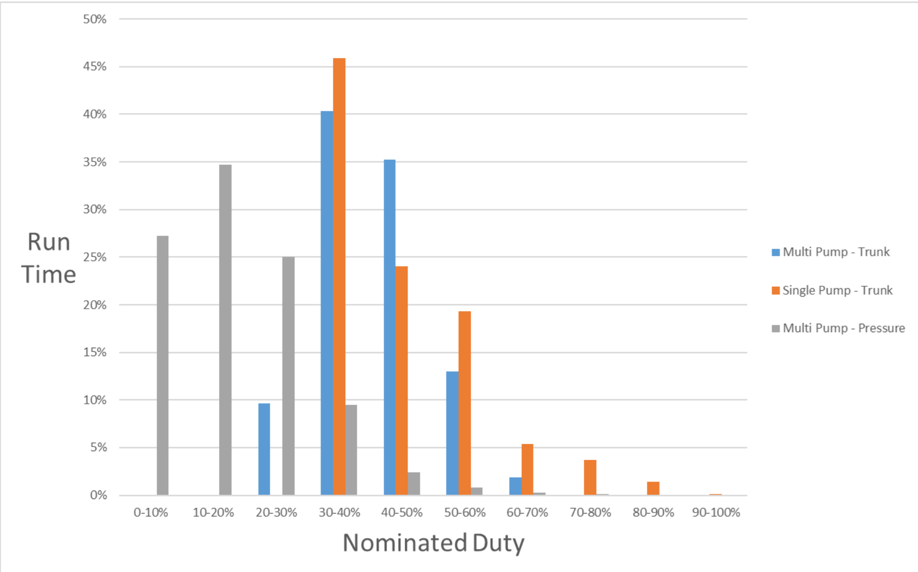

Figure 1 Percentage of run time at proportion of design duty over 12-month period

Barringer investigated the relationship between the flow rate and time to failure of centrifugal pump seals [1]. Graphs that illustrate their findings are readily available and typically illustrate a bell-shaped curve overlaid on a Q-H pump characteristic curve. The bell curve represents the relationship between the flow rate as a proportion of the flow rate at the Best Efficiency Point (BEP) and the Mean Time Between Failures

(MTBF). Likewise, the International Standard for mechanical vibration [2] of rotodynamic pumps illustrates a very similar concept.

Both the graph constructed by Barringer and that used in the international standard concur on two critical points:

- Operation at Q_{BEP} causes the least wear/vibration, and
- $Q > Q_{BEP}$ (also known as 'operating to the right of BEP') causes significantly more wear/vibration than $Q < Q_{BEP}$ (similarly known as, 'operating to the left of BEP')

3 Methodology

3.1 Determination

For this desktop case study, a simplified relationship between flow rate and MTBF will be utilized. A linear proportional relationship will be used for the operating range to the left of BEP, where nil flow equates to nil time between failures (although it is acknowledged that this is not strictly correct) and at Q_{BEP} the MTBF will be maximum. Similarly, a linear inversely proportional relationship of twice the gradient will be used to the right of BEP, where 150% of Q_{BEP} will equate to nil time between failures.

$$\underset{0 \leq Q \leq Q_{BEP}}{\mathrm{MTBF}\{Q\}} = MTBF_{Q_{BEP}} \times \frac{Q}{Q_{BEP}} \quad (1)$$

$$\underset{Q_{BEP} \leq Q \leq \infty}{\mathrm{MTBF}\{Q\}} = MTBF_{Q_{BEP}} \left[1 - 2 \times \left(\frac{Q - Q_{BEP}}{Q_{BEP}}\right)\right] \quad (2)$$

3.2 Unit of measurement

Seemingly the most relevant metric for both specific energy and cost of refurbishment would be cost per unit volume. Unfortunately, the cost for both is continually changing due to uncontrollable factors. However, once the algorithms are programmed into software, the output is readily changeable to incorporate current costs. It is the combined effect of energy consumption and rate of wear being examined in this paper, and as such cost assumptions are required. Moving forward, these assumptions will be:

- Electricity → 26c per kWh (Inclusive of all tariffs)
- Pump refurbishment → \$40 000 every 50 000 hours if operated at Q_{BEP}

While this is a straight forward conversion for Specific Energy, it is not so for the cost of refurbishing the pump, which is the physical representation of the effect of wear.

A relationship between the cost of refurbishment and the MTBF follows:

$$Refurbishment\left({}^{Cost}/_{Volume}\right) = \frac{Refurbishment\ Cost}{MTBF} \times \frac{1}{Q} \quad (3)$$

Using this relationship is conjunction with the varying rate of expected wear represented in equations 1 & 2 yields the cost of refurbishment across a range of flows and pump heads to be determined.

The system curve to be analyzed (figure 2) has been constructed to intersect the full-speed Q-H curve at the BEP. The static portion of the system curve has been chosen to best demonstrate the effect being analyzed by this paper.

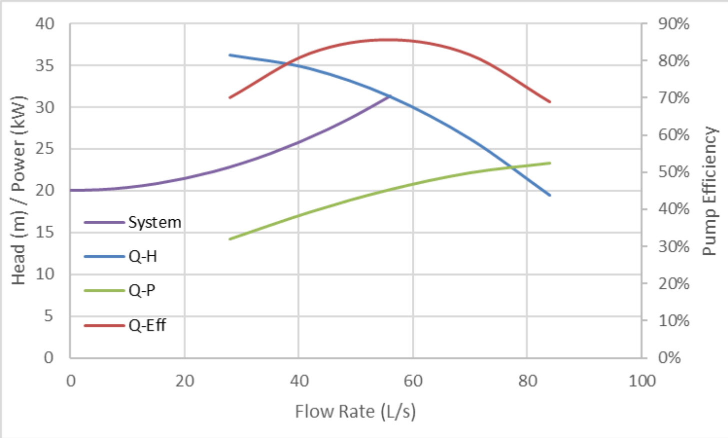

Figure 2 Pump Characteristic Curve and System Curve used in Case Study

Utilizing the methodologies laid out in 'Optimizing the speed of centrifugal pumps' [3] the refurbishment cost and specific energy can be determined for any combination of flow and head within the range of operation for the pump.

Analyzing the combination of pump and system shown in figure 3 reveals minimums for each expense, and that the cumulative expense has a third minimum.

Table 1 Specific Energy and Refurbishment expressed in $/ML

Q (L/s)	H (m)	N (% full Speed)	Pump Efficiency	Es ($/ML)	Refurbishment ($/ML)	Total ($/ML)
20	21.4	76.8%	67.7%	22.46	18.35	40.80
25	22.3	78.6%	74.2%	21.25	12.31	33.55
30	23.3	81.0%	78.8%	20.92	9.08	29.99
35	24.4	83.9%	81.8%	21.17	7.15	28.32
40	25.8	87.2%	83.7%	21.83	5.92	27.75
45	27.3	90.9%	84.8%	22.83	5.08	27.90
50	29.0	94.9%	85.4%	24.10	4.48	28.58
56	31.3	100.0%	85.6%	25.94	3.97	29.92

Moving forward, the pump characteristic Q-H curve can now be analyzed in its entirety.

3.3 Graphical representation

Using discreet intervals across a suitable range of flow rates and pump head, and evaluating the major expenses for each combination of Q & H, allows for a graphical representation as shown in figure 3.

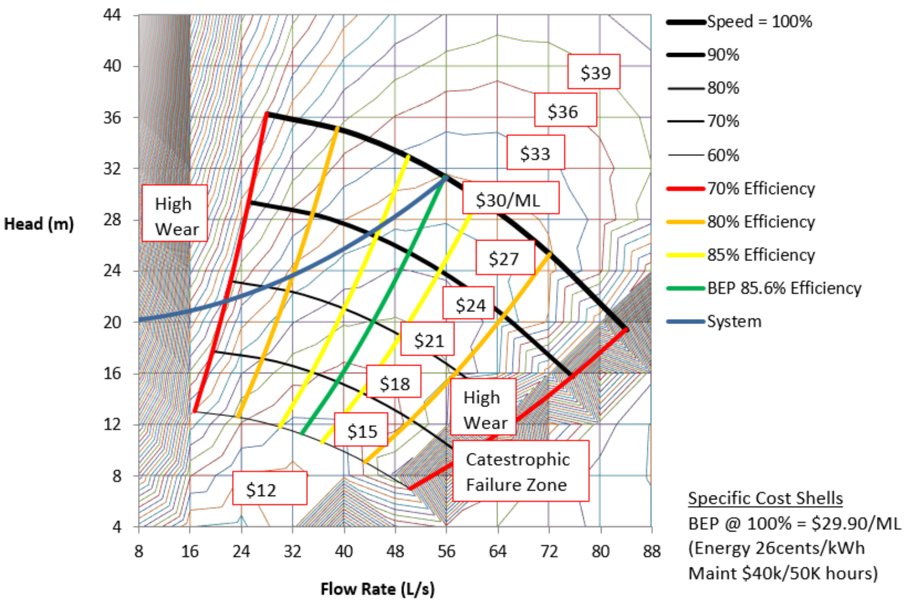

Figure 3 Combined cost of energy and refurbishment across entire operating range of pump

3.4 Monitoring specific energy

Specific energy can easily be monitored by trending the power divided by flow rate, but by trending the variance between operating specific energy and what it could be if the pump were in as-new condition may allow for maintenance activities to be prioritized. For the purpose of this case study, a decrease in flow of 10% and 20% will be reviewed and the specific energy lost compared to the pump and system being in original (as-new) condition, operating at a slower speed to achieve the same flow rate.

The two main mechanisms that may reduce flow are identified by the head developed by the pump in comparison to what head should be developed if the pump and system were in ‘as-new’ condition. Essentially, the flow reduction can be a manifestation of the pump developing more head than expected, less head than expected, or a combination of the two. For all iterations, checking the power will ultimately confirm where the pump is operating on the Q-H pump characteristic curve.

The results from a flow reduction of 10% and 20% for both increased and decreased head have been summarized in Table 2 following:

Table 2 Specific Energy increase as a result of decreased flow

Q Reduction	**Specific Energy Increase at Observed Flow Rate** - compared to pump and system in as-new condition and operating at reduced speed to achieve same flow rate.	
	Head Increase	Head Decrease
10% - 50.4 L/s	13%	25%
20% - 44.8 L/s	42%	54%

4 Discussion

Table 1 reviews the refurbishment cost per unit volume pumped, a similar and equally relevant metric in terms of controlling life cycle cost as specific energy. The review across the range of flows and corresponding head for the given system demonstrates that the minimum refurbishment cost does not coincide with the minimum energy cost, and instead correlates with the maximum pump efficiency. Further to this, the cumulative cost minimum does not coincide with either minimum specific energy or minimum refurbishment cost and highlights the value in reviewing both expenses.

Figure 3 illustrates the combined effect of refurbishment cost and specific energy for the entire range of operation for the pump. This demonstrates an unexpected finding, the reduction in specific energy that occurs at increased flow rates for a given speed offsets the increased rate of wear typically expected to the right of the pump's BEP.

Table 2 demonstrates that for the pump and system being analyzed, there is a marked difference between the observed Head increasing and decreasing, and likewise between a 10% and 20% reduction in observed flow. This demonstrates the value of monitoring performance and benchmarking against as-new performance as a maintenance tool.

5 Conclusion

The inclusion of the refurbishment cost alongside the energy cost in terms of $/ML pumped across the entire range of operation achievable by a pump clearly demonstrates modes of operation that will cause significant increases in the cost of asset ownership.

This paper also demonstrates the inherent value in continuous monitoring of pump operation as VSDs are particularly proficient at hiding performance losses in processes controlled by flow rate.

6 References

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