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Improving the design life cycle efficiency of wastewater treatment plant inflow pumps

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Abstract—This paper evaluates data from 10 centrifugal pumps in a large wastewater treatment facility to illustrate the impact of pump design, selection, maintenance, and operation on system efficiency. The paper explores the efficiency impact of several interventions and qualitatively presents trade-offs to implementation. Of the interventions explored, energy savings up to 3% were identified representing 239,000 kWh annually.

Keywords—variable speed pumps, pump energy efficiency, pump system optimization, wastewater treatment, product lifecycle, performance metrics

I. Introduction

Centrifugal pumps are ubiquitous in fluid systems such as clean water distribution, wastewater treatment, pumped hydro energy storage, building HVAC systems, petroleum extraction, mining, and crop irrigation. Globally, pumps consume hundreds of billions of kilowatt hours of electricity each year. In the US, pumps consume an estimated 6% of U.S. electricity, equivalent to 230 billion kWh annually[1], about the output of 58 Hoover Dams [3].

This paper begins with key concepts from the literature on evaluating and improving pump system efficiency. Using this background, we evaluate data from 10 centrifugal pumps in a large New England wastewater treatment facility to understand the influence of pump design, selection, maintenance and operation on system efficiency. We quantitatively explore the efficiency impact of interventions and qualitatively present trade-offs to implementation.

The methods and recommendations developed from this case study can potentially be applied more broadly to other pumping systems and to motivate pump design and system operation research.

II. Background

A. Pump Design Life Cycle

The pump lifecycle, shown in Fig. 1, implies strong coupling between design, selection and operation. For example, physical dimensions, including clearances to enhance robustness, in the design influence operational efficiency, while knowledge of the operational duty cycle influences the designed pressure and flow. Pump selection depends on knowledge of the operational system curve. Operational flexibility depends on whether controls such as variable speed drives are installed with the pumps. Furthermore, pump maintenance and monitoring can substantially reduce energy consumption. Given the wide range of operating pressures, flows, and speeds, advanced operational and pump control can further reduce energy consumption [5, 10, 11].

Fig 1. Available pumps influence component selection, which then influences system operation. Conversely, information about system operation influences component selection. Both, in turn, influence the design of new pumps. Pump simulation image (left) used from SimScale GmbH with permission.

Pump system efficiency is maximized by a combination of improved design, pump selection, and adaptive control, which includes accounting for wear. Data collection and analysis provides a foundation to enable improvements at each stage as well as closing the loop on the pump lifecycle.

B. Efficiency Metrics for Real Systems

Pump systems operate over a range of flow and pressure conditions. In contrast, centrifugal pump manufacturers typically specify a single design point for most efficient operation; the best efficiency point (BEP). This is an important parameter because system fluctuation away from the BEP leads to energy losses and increased wear. Fig. 2 shows the traditional pump and system characteristics intersecting at the BEP. It also visualizes shaded ranges of variation about the characteristics. Energy losses can be reduced throughout the design life cycle:

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[1] The 1998 US Industrial Electric Motor Systems Market Opportunities Assessment [1] states that motors consume 23% of electricity and pumps represent 25% of motor consumption. Therefore, we estimate that pumps consume 6% of US electricity sold. The Department of Energy [2] records show in 2018, 3.9 trillion kWh of electricity was sold in the US. Thus, 232 billion kWh is a reasonable estimate of annual pump electricity usage.

- Design: Hydraulic geometry can create a broad efficiency curve allowing for efficient operation, typically between 85% to 110% of the BEP flow.

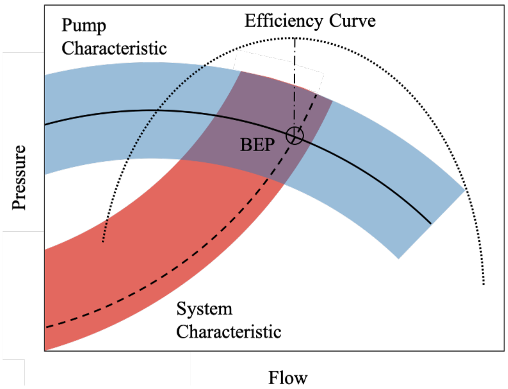

Fig. 2 Traditional model of pump operation showing the pump curve, system characteristic, and an efficiency curve with ranges of operation shown by the shaded blue and red curves.

- Selection: Best practice characterizes the system and selects a pump such that the pump characteristic intersects the system at the BEP. Selection that accounts for how the real system is operated can have significant impact on lifetime efficiency.
- Operation: Advanced control, like variable speed drives, can shift the pump characteristic to better meet changes in the system curve.

These strategies lead to more efficient operation, improved equipment lifetimes, and lower operating and maintenance costs.

Although the BEP is the standard metric, it does not capture the efficiency of the system operating over a range of conditions over time. True weighted efficiency (TWE), defined in Eq. 1, is the energy weighted average efficiency for a pump [4]. TWE directly measures energy wasted and enables engineers to compare pumps by calculating energy savings while accounting for the pump design and the system variations. The Pump Energy Index (PEI), promoted by both the Hydraulic Institute and the U.S. Department of Energy (USDOE), utilizes a similar method, but compares a pump with an aggregate baseline for a pre-determined load profile. A detailed review of pump efficiency metrics can be found in Dahl's 2018 paper [4]. Utilizing metrics, like TWE, during design, selection, and operation will better inform decisions to improve efficiency.

$$\eta_{TWE} = \frac{\sum P_o t_o}{\sum \frac{P_o}{\eta} t_o} \qquad (1)$$

C. *Modern Methods of Imcreasing Efficiency*

While pump design and application are mature areas, Shankar et al [5] present a comprehensive review of pump efficiency enhancement opportunities primarily focused on selection and operation. Gülich [6] presents efficient design methodologies to address the nuances of hydraulic, volumetric and mechanical efficiency. The Pump Handbook [7] extensively covers pump performance, design, selection, maintenance, and operation.

Variable speed drives (VSD) improve pump operational efficiency because it allows operators to adjust the speed to control either the flow or efficiency [8]. Increased availability of data collection and monitoring for control and optimization will also be transformational. Notably, there are examples of using data and optimization to improve wastewater plant operations. For example, Zhang et al. present methods for optimizing the control of a wastewater plant that could theoretically lead to as much as energy 25% savings [9]. Similarly, Torregrossa and Capitanescu share their application of heuristic optimization algorithms in one paper to reduce the energy consumption of a wastewater treatment plant, and fuzzy logic in another [10,11]. These works set the stage for arrays of pumps in a system to be better controlled and maintained to increase efficiency.

III. Wastewatre Treatment Plant Case Study

A. *Inflow Pump Station Data*

Pump operating data were acquired from a large New England wastewater treatment plant inflow pump station. The pumps consume 18.5 million kWh annually, which is approximately 1% of the state's annual electricity consumption. The system consists of ten Fairbanks Morse 42" model 2414 vertical centrifugal sewage pumps installed with variable speed drives [12]. Each pump was originally rated for 110-150 MGD[2] at 150 ft of head at 400 rpm, 100% speed. This represents an installed capacity of approximately 2610 kW (3500 HP) per pump. Raw hourly data for pump status (on/off), flow (MGD), power (kW h), motor speed (RPM), and pump suction tunnel elevation (feet) were collected for each of the 10 pumps for a period of five months between August and December of 2019. Data were converted to metric units. Data where the pumps were off were removed from the set, resulting in 7875 data points.

Pressure data available had been previously measured by analog gauges and manually recorded, and hourly data were unavailable. The static pressure rise across each pump was estimated from the difference in water column height at the inlet and outlet. The pump outlet is connected to the relatively constant grit chamber elevation of 47.85 meters. The inlet water elevation was calculated by subtracting the dynamic head ($\frac{1}{2}\rho v^2$) associated with a 48" pipe diameter and a given flow from the recorded static pressure on the inlet side. The hydraulic power $P_{hydraulic}$ and wire-to-water efficiency η of the pump at each point were calculated as shown in (2) and (3) where Q is the flow and $P_{electrical}$ is the electrical power input to the motor. Friction losses in the pipes and small fluctuations in the grit chamber elevation are the primary sources of error in this efficiency calculation.

$$P_{hydraulic} = Q\,\Delta p_{static} \qquad (2)$$

$$\eta = \frac{P_{hydraulic}}{P_{electrical}} \qquad (3)$$

Fig. 3 shows the relationship between pump pressure, speed, flow, and efficiency at the wastewater plant. Iso-speed curves are shown on the pressure-flow plot. It is evident that this real system with variable speed control is more complex than the traditional pump curve representation in Fig. 2. It is likely that the two horizontal bands result from the control chart elevations of two inflow tunnels to the pump station,

[2] MGD: Million gallons per day

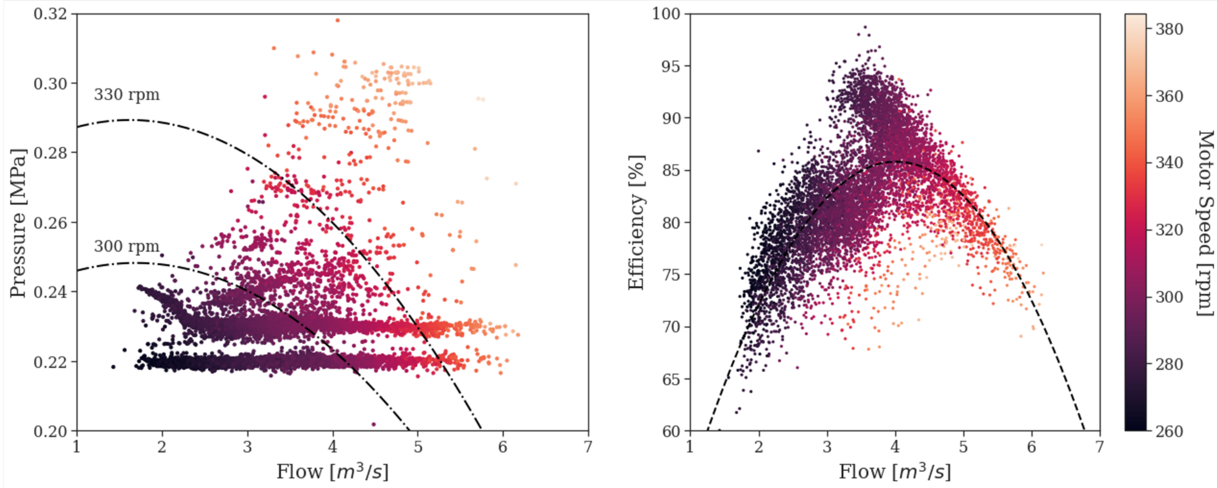

Fig. 3 Pump performance data (n=7875) shows range of operating conditions and efficiencies during a five month period. Labeled trend lines show lines of constant speed and the best fit efficiency curve. Pressure is the static pressure rise across the pump.

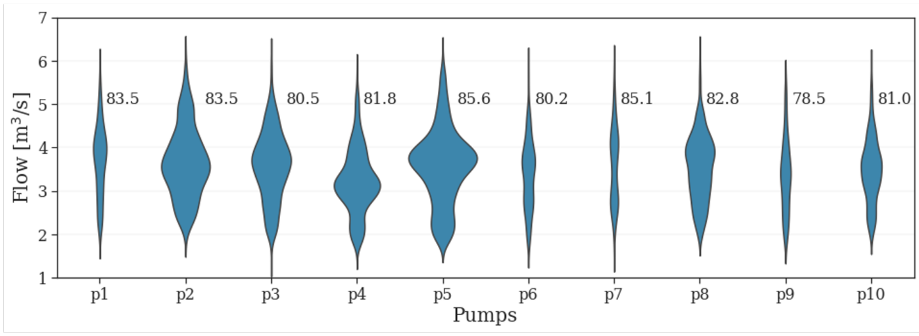

Fig. 4 Violin plots compare flow profiles for 10 pumps. Labels indicate the TWE for each pump to compare the duty cycle to efficiency.

TABLE I. SUMMARY STATISTICS COMPARING PUMP OPERATION

Statistics	**Pumps**									
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
TWE [%]	83.4	83.4	80.5	81.8	85.5	80.1	85.1	82.8	78.5	81.0
Mean efficiency [%]	83.3	83.4	80.4	81.4	85.6	80.0	85.0	82.5	78.2	80.8
Std deviation [%]	4.1	4.1	4.8	5.5	5.9	4.8	4.8	5.1	5.0	5.0
Operating time [%]	4.4	16.3	13.2	15.5	23.0	4.5	2.7	9.9	3.5	7.0
MREP flow [m^3/s]	3.5	3.6	3.6	3.5	3.8	3.6	3.6	3.8	3.4	3.5
MREP pressure [kPa]	223	231	225	225	235	224	225	225	225	226
MREP speed [rpm]	287	288	290	286	293	289	286	292	290	288

around 24 and 25 feet respectively. Inflow to the pump station is comprised of both sewage and storm water. The majority of data points (82% of points are less than 0.24 MPa) likely represent baseline sewage generation occurring along the two bands. The higher pressure points likely correspond to intermittent inflows caused by weather events such as rainfall or snow melt.

B. Analysis

The efficiency-flow plot shows a broad range of efficiencies around the line of best fit. Given that efficiency was estimated from parameters in the dataset, it is likely that real-time efficiency information is not available to the operator. In order to investigate the variation in efficiency, we explored variation between pumps, over time, and in control.

The violin plots in Figure 4 compare the flow histograms for the 10 pumps. While there is a general bulge between 3-4 m^3/s, the pumps show distinct operational differences. Pumps 5 and 2 were operated the most over the period of data collected, while pumps 6, 7 and 9 were rarely operated.

The summary statistics for pump operation and performance are presented in Table 1. The maximum recorded efficiency point (MREP) flow, pressure and speed were determined by the point at which the maximum efficiency was recorded.

Several insights are drawn from these statistics. There is an 8% difference in TWE between pumps 5 and 9. The energy weighted efficiency and mean efficiency are closely correlated. Pumps 2, 4 and 5 are operated most often, while pumps 1, 6, 7, and 9 are rarely operated during the period of data collection. Pump 7 is second most efficient but rarely operated. This exemplifies the need for automatic control strategies to consider heuristic knowledge of veteran operators. Simply using pump 7 more could represent a substantial energy savings. Close agreement between the pumps' BEP flow, pressure and speed indicates a designed best efficiency around 290 rpm, 3.6 m^3/s, 226 kPa.

Three targeted efficiency improvement strategies are presented: upgrading all pumps to pump 5 efficiency, installing a smaller pump for lower flows, and adding additional means of control to avoid high speed, low efficiency points as seen in Fig. 3.

In order to calculate the TWE for all pumps upgraded to pump 5 efficiency, the data were fitted to a second order polynomial. The total energy weighted efficiency was then calculated using the pump 5 efficiency curve for all data points. We found a 3.1% improvement in energy weighted efficiency if all pumps operated at pump 5's efficiency, representing 239,000 kWh annual savings. Assuming $0.10 per kWh energy cost, this represents an annual savings of $23,900. The cost of electricity for a large industrial plant is often more complicated than a simple per kWh basis because of incentives and costs associated with peak energy use. The wastewater treatment plant engineers shared that their internal estimates for cost savings were more than 5x this estimate. Using pumps 5 and 7 most often, and pumps 1, 2 and 8 second most is a viable energy saving strategy.

Using a combination of pump sizes to cover different flow segments is another strategy for improving energy efficiency. The data were separated into two regions: a low flow region less than 2.5 m^3/s and the rest of the flow. We constructed a reasonable efficiency curve for a smaller pump to operate at flows between 0.5 and 2.5 m^3/s. Using this model we found a 1.3% improvement in system efficiency. Implementing pony pumps and combinations of pump sizes is a widely recognized strategy by practitioners, but adoption is limited by the available footprint in wastewater facilities.

This analysis demonstrates the utility of metrics like mean efficiency and energy weighted efficiency in operational control. While there is little difference between mean efficiency and energy weighted efficiency in this dataset, there are other systems where that is not the case [4].

C. Efficient and Operational Control

The right plot in Fig. 3 provides two insights about pump operation. The variation in pump efficiency around the best fit line indicates that VFD is used to achieve desired operation at the expense of efficiency. If efficiency could be directly controlled, the efficiency values would form a tighter line than shown in Fig. 3. Additionally, it shows that the pumps were oversized for typical operation because speeds much lower than the nominal speed of 400 rpm are the most efficient. This is expected since pump over-sizing is standard practice to meet maximum flow requirements.

Based on these observations, we propose an axiom of pump operation: operational control (desired flow at a desired pressure) and efficient control (BEP operation) cannot be achieved by the same degree of freedom or means of control. Optimizing both objectives requires a minimum of two separate degrees of freedom. This implies that a second element of the pump's operation, geometry or time in addition to impeller speed, must be controlled to maximize energy efficiency and operational life while giving the operator flexibility to effectively operate their system. This axiom would re-affirm the need for widespread use of VFD and motivates research into additional methods for industrial-grade pump control.

Fig. 5 shows pumps intelligently operating in parallel, controlled to meet flow demand, or to optimize for efficiency. Current means of control include variable speed drives and turning combinations of pumps on and off. A connected feedback system could continuously measure flow, pressure, power and speed to calculate the efficiency and optimize a control scheme for efficiency while constrained by operational requirements.

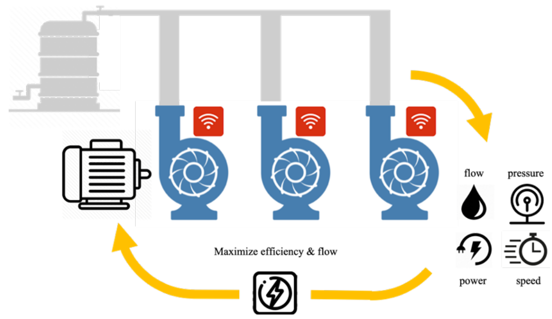

Fig. 5 Parallel pump operation with connected feedback and control loop.

IV. Conclusion

This paper identified areas for better cooperation between pump operators, pump engineers in industry, and researchers in academia. Reviewing real data from a wastewater treatment plant gives context to developments in the field.

Pumps operate within many different contexts, and there is variability even between equivelant wastewater plants. Across contexts, facilities can benefit from implementing continuous measurement of power, speed, flow, and static pressure rise, which enables tracking efficiency metrics. This could provide operators and management evidence to identify and justify efficiency improvements.

In this case study, lack of real-time pressure data limited the ability to precisely calculate the real-time efficiency but the potential gains identified were significant and illustrates the need for the the pumped systems community to identify and address barriers to implementing best practices used by many other industries. Against the backdrop of pumps being a mature technology, the community should also advocate for the advancement of research on the control and operation of pumps including collection of a wide array of data across many systems to inform good practice, design, and efficient automated control systems.

Acknowledgment

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