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Correction of the EPANET inaccuracy in computing the efficiency of variable speed pumps

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Abstract

One attractive possibility for saving energy in water distribution systems is the introduction of variable speed pumps (VSPs). However, to assess the cost effectiveness of using VSPs, a correct estimate of VSP energy consumption, and therefore efficiency, is essential. This task involves estimating the efficiency of various components: pump, motor and variable speed drive. Hydraulic solvers, which are used to check the hydraulics of the system, usually use the affinity laws to describe the pump behavior in a VSP pumping system. This paper demonstrates the inaccuracy of the popular hydraulic solver EPANET 2, which does not properly take into account the affinity laws in the efficiency computation when the speed changes for VSP operations. The correction of the code is presented and an additional improvement of the toolkit in order to directly retrieve the efficiency is introduced.

Keywords: efficiency; variable speed pump; water distribution system; EPANET.

Introduction

Increased energy costs and concern for environmental sustainability have boosted interest in saving energy. In water distribution systems (WDSs), the reduction of energy consumption due to pumping can be obtained by replacing fixed speed pumps (FSPs) with variable speed pumps (VSPs) (Lingireddy and Wood, 1998). Recent improvements in VSP technology, such as improved efficiency and lowered costs of VSPs (Pemberton, 2005), are contributing to increased interest in the application of this technology to WDSs. VSPS are pumps with a motor that is able to be linked to a variable speed drive (VSD). The VSD is able to modify the frequency of the electrical signal so that the pump can run at different speeds, which in turn will change the pump performance curve. However, the introduction of a VSD to modify the pump speed decreases the wire-to-water efficiency, and the economics of investment in VSP systems require evaluation.

The assessment of VSPs is often based on simulations that model a WDS in which variable speed pumps could be installed and operated. Evaluations must take into account the different efficiencies of motor, variable speed drive and pump when speed and load are changed (Bernier and Bourret, 1999; Walski, 2001; Walski et al. 2003; Walski, 2005; Marchi et al. 2011). Although all elements of a pumping system must be factored into the assessment, pumps typically have a lower efficiency than either VSDs or motors, and therefore they have more of an influence on the wire-to-water efficiency. It is necessary, therefore, to represent the pump behaviour as accurately as possible when computing efficiency.

The pump efficiency of a VSP system is usually estimated using affinity laws which describe the mathematical relationship between the variables involved in pump performance, such as flow, total head and power, and the pump speed. However, this paper shows that the popular hydraulic solver EPANET 2 (Rossman, 2000) is inaccurate in computing the efficiency of this type of pump. After the description of the affinity laws, an example will show this inaccuracy and a correction to the software is proposed. Note that in these two sections, only the pump efficiency will be considered. In the last section, motor and VSD efficiencies will be briefly discussed for completeness.

Dimensionless pump numbers and affinity laws for VSPs

The dimensionless pump numbers are used to described the behaviour of similar pumps when the pump speed, *N* (rpm), or the impeller diameter, *D* (m), is changed (Eq. 1).

$$\text{a)}\quad C_Q = \frac{Q}{N \cdot D^3} \qquad \text{b)}\quad C_H = \frac{gH}{N^2 \cdot D^2} \qquad \text{c)}\quad C_P = \frac{P}{\rho \cdot N^3 \cdot D^5} \qquad \text{(Eq. 1)}$$

where C_Q, C_H, C_P are the dimensionless flow, head and power, respectively, Q, H, P are the pump flow (m^3/s), head (m) and power (W), respectively, ρ is the liquid density (kg/m^3) and g is the acceleration of gravity (m/s^2).

Eq. 1c indirectly represents the pump efficiency, as the power is proportional to the product of flow and head divided by the efficiency, η.

$$P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta} \qquad \text{(Eq. 2)}$$

C_Q, C_H, C_P are constant for similar pumps. If a pump is run at a different *N* or with a different *D*, the pump characteristics are represented by unique curves in terms of both the dimensionless pump curve of C_H-C_Q and the dimensionless efficiency curve of η-C_Q. (Figure 1).

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The affinity laws (Eq. 3) are a particular case of dimensionless pump characteristics which describe pump speed change. In particular, Eq. 3 show that flow, head and power are a linear, quadratic and cubic function respectively of the pump speed, *N*.

$$\text{a)}\quad \frac{Q_1}{Q_2}=\frac{N_1}{N_2} \qquad \text{b)}\quad \frac{H_1}{H_2}=\left(\frac{N_1}{N_2}\right)^2 \qquad \text{c)}\quad \frac{P_1}{P_2}=\left(\frac{N_1}{N_2}\right)^3 \quad \text{(Eq. 3)}$$

where the subscript 1 and 2 refer to two different pump speeds.

EPANET, as well as some other hydraulic solvers, do not use Eq. 1c or 3c directly to compute the power of a pump run at different speeds, but instead use the curve of efficiency versus flow at the nominal pump speed, which is commonly provided by the manufacturer.

When the pump speed is reduced, the efficiency curve plotted versus the flow Q actually shifts to the left and narrows (in contrast to the η-C_Q curve that remains constant), but maintains the same best efficiency point (BEP) as assumed by Eq. 1c and 3c. The behaviour of the η-Q curve at two different speeds can be seen in Figure 2. It should be noted that, when the speed is decreased, the efficiency curve narrows because the range of flows over which the pump can operate is reduced in proportion to the speed according to Eq. 3a.

The inaccuracy in EPANET in computing VSP efficiency

EPANET's inaccuracy in computing the efficiency (and therefore the power) of variable speed pumps will be explained using the example network shown in Figure 3, where values have been chosen to provide illustrative figures. Velocities are in an acceptable range of <2 m/s. The same concepts can be applied to more complex systems or to systems with high static heads. In this regard, it is worth noting that Eq. 3 predicts only the new pump curves, H-Q and P-Q (or η-Q), while the operating point is still defined by the intersection of the pump curve with the system curve. For this reason, in systems with high static heads, the

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efficiency of pumps operated at reduced speeds can be markedly lower than the efficiency of the pump operated at the nominal-speed (BPM et al. 2003; Hydraulic Institute et al. 2004) because of the rapid flow decrease when the pump speed is reduced.

In the example, the pump P4 has been designed to pump water from the reservoir to the tank, resulting in the hydraulic grade line shown with the continuous gray line in Figure 3 when the pump is run at full speed ((N_1 = 1450 rpm).

It is assumed that the pump can be run at 1110 rpm ($0.75 \cdot N_1$) during the period of low demands. This results in decreased head losses as shown by the hydraulic grade line (dash line in Figure 3). At the reduced speed, the pump curves (H-Q and η-Q) are modified using Eq. 3: as shown in Figure 2, the pump is now working at point A (H = 70.8 m, Q = 95 L/s). EPANET 2 correctly models the changes in the head-flow curve at the lower speed and therefore it identifies the point A. However, there is an inaccuracy in the power computation. EPANET 2 continues to use the efficiency curve at the nominal pump speed and, therefore fails to correctly modify the curve. In fact, as previously explained, only the η-C_Q curve does not change as a function of the speed, whereas the η-Q does change. The software computes a pump power of 86.4 kW, corresponding to a flow=95 L/s, head=70.8 and an efficiency of 76.3% (point B). However, in reality, at the new lower speed, pump power is actually equal to 78.3 kW, because the efficiency of the operating is η=84.2% (point C).

Such inaccuracy in the popular software can lead to either an underestimation or an overestimation of the required energy, depending on the system configuration, including the position of the operating point at the nominal speed, and the difference in flow at the reduced speed. The correction of this inaccuracy is straightforward, as it requires only the 'shifting' of the efficiency curve according to the affinity law related to flow, Eq. 3a, or, equivalently, by considering η vs Q/ND^3. A proposed correction of EPANET 2 source code is shown in Appendix A of the supplemental data.

In addition, a further improvement of the EPANET toolkit code is proposed in Appendix B of the supplemental data to directly retrieve the efficiency of the pump operating point, whereas at the moment only the power is given in output. In fact, it is useful to check at which minimum efficiency a pump (either FSP or VSP) operates because very low efficiencies are often related to increased pump deterioration.

Discussion about the modeling of VSPs

The correction of EPANET presented here is only related to the modeling of the pump efficiency using the affinity laws. However, many other factors have to be considered for accurate assessment. First of all, the affinity laws can predict the pump efficiency with a good approximation only for a pump speed down to about 70% of the nominal speed (Sârbu and Borza, 1998).

Secondly, to assess the efficiency of VSPs, the wire-to-water efficiency has to be assessed. Therefore, all the components that impact the energy initially available have to be considered. As pumps are mostly run by electric motors, motor and variable speed drive efficiencies have to be assessed. Although there is software able to do so (e.g. WaterGEMS, Bentley Systems), these two components of VSPs are not currently modeled by EPANET. Motors usually can maintain high efficiencies if they are operated at loads not too far from the nominal value. Losses in variable speed drive depend on the type of VSD used and the speed reduction. However, due to the energy dissipation, in some cases a fan to cool the VSD is required, resulting in additional energy consumption.

Note that the wire-to-water efficiency can be greatly reduced by each of the three components mentioned. Therefore accounting only for the pump efficiency has to be seen as a part of the evaluation of VSP effectiveness.

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Conclusion

An accurate prediction of variable speed pump efficiency is essential for assessing the suitability of different options for reducing the energy consumption of electric and fuel-driven pumps. The work presented here focused on modeling the pump efficiency when a variable speed pump is operated at a reduced speed.

Results show that the popular hydraulic solver EPANET 2 does not take into account the affinity laws to compute pump efficiency when the pump speed is reduced. Instead, the software uses the original efficiency curve at the nominal speed. Therefore the pump power and the energy consumption retrieved, which are inversely proportional to the efficiency, are incorrect. In particular, the efficiency can be either overestimated or underestimated depending on the new operating point and on the efficiency curve at the nominal speed. A correction of the source code of the EPANET software is proposed in order to scale the efficiency curve according to the affinity laws. In addition, a modification to the EPANET software to directly retrieve the efficiency from the toolkit is presented.

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Figure2

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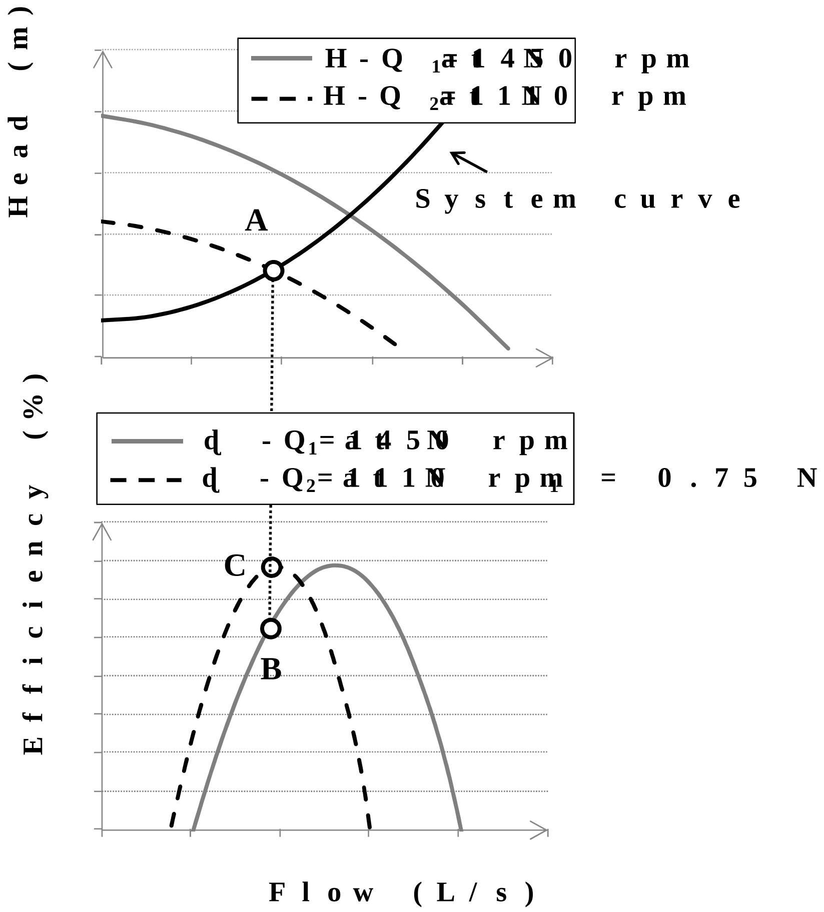

Figure3

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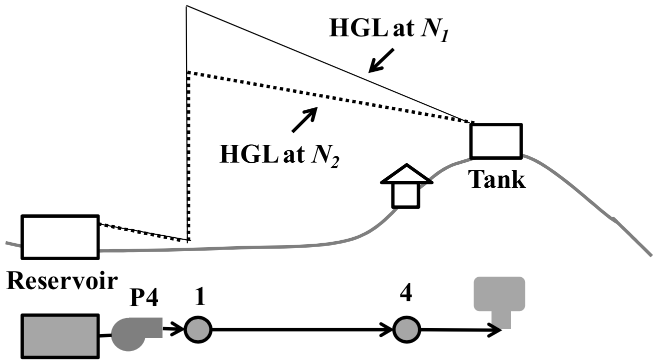

Figure 3. Layout of the example network (above) and EPANET representation (below). HGL means hydraulic grade line.