Implementation of the mechanical power input calculation algorithm for a group of pumps in OWA EPANET

Tomasz Janus

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1 Introduction

The task of this project was to provide an extension to the open source EPANET project that would allow calculation of the efficiency and the power characteristics of a pump group using the equations derived and described in [1]. The current version of EPANET, as of 01/03/2020 calculated the the energy consumption of a pump assuming a single variable-speed pump. The program was extended to take into account groups of equal variable speed pumps operating at the same speed. Implementation of the equations from [1] was requested by the EPANET community in Issue 574 on the dedicated GitHub branch at OpenWaterAnalytics/EPANET. The issue was picked up by Water Software Systems Groups at De Montfort University in Leicester, UK. The current version of EPANET was forked and after successful implementation of the equations and approval of the pull request, new commit was submitted by Water Software Systems on provide date.

2 Power input calculation methodology for a variable speed pump in OWA EPANET

The current version of OWA EPANET, as described in [2], calculates the power supplied by the pump (in kW or hp) with the following two alternative methods:

1. In a simplified way assuming that the pump supplies the same amount of energy regardless of the flow. The pump is treated as a constant energy device and thus, supplies a constant amount of energy to the fluid per unit time for all combinations of flow q and head Δh. This (constant) power supply is specified in the .inp file in the [PUMPS] section as property POWER. Is it correct to assume that Δh is then calculated from the supplied power? How is this done? Is this the electrical power input or mechanical power input? [Ask L. Rossman].

2. From the provided pump curve and the efficiency curve. The pump curve is provided for the pump as ID label of the pump curve used to describe the relationship between the head delivered by the pump and the flow through the pump. The efficiency curve represents the pump's wire-to-water efficiency (in percent) as a function of flow rate. It is given for the pump as the ID label of an efficiency curve. If not supplied than the global

pump efficiency supplied with the project's Energy Options is used. How is the power calculated from the two curves? [Ask L. Rossman].

2.1 Pump curve in OWA EPANET

The pump curve can be specified in three different ways:

1. By providing a single point $(\Delta h^*, q^*)$ representing the pump's desired operating point. Two more points are automatically added by the software $(1.33\,\Delta h^*, 0)$ and $(0, 2\,q^*)$
2. By providing three points $(\Delta h_1, q_1)$, $(\Delta h_2, q_2)$, $(\Delta h_3, q_3)$ where one point should define low flow conditions, the second should describe the desired operating point, whilst the third should denote the maximum flow conditions, i.e. head and flow at maximum flow.
3. By providing either two or four or more $(\Delta h, q)$ pairs (points).

In case of 1 and 2 OWA EPANET defines the entire pump curve by fitting a power equation:

$$\Delta h = A - B\,q^C \tag{1}$$

where A,B, and C are the calculated constants (parameters). Ask L. Rossman how this is done.

In case of 3 the obtained pumped curve is piece-wise linear. Ask L. Rossman how this links to hydraulic calculation algorithms.

2.2 Variable speed pumps in OWA EPANET

OWA EPANET models a variable speed pump by specifying its relative speed s, i.e. the speed relative to the one for which the original pump curve was supplied. By definition, the original pump curve supplied to the program has a relative speed setting $s = 1$. If the pump speed doubles, then $s = 2$; if the pump is run at half speed, then $s = 0.5$, etc. Changing the pump speed shifts the position and shape of the pump curve. The speed of the pump can be constant or changing according to the specified time pattern. Given the pump characteristic for the nominal speed $\Delta h = f(q)$, the new characteristic at the relative speed s is given as:

$$\Delta h/s^2 = f(q/s) \tag{2}$$

which is consistent with the equations provided in [1]. In OWA EPANET, the power curve approximation given in Eq. 1 becomes

$$\Delta h/s^2 = A - B(q/s)^C \tag{3}$$

2.3 Efficiency and the efficiency curve in OWA EPANET

Pump efficiency in OWA EPANET is either supplied as a constant (fixed global pump efficiency) or as a curve determining the pump's wire-to-water efficiency $\eta = \eta(q)$. The pump efficiency curve is supplied as a series of points $(\eta(q), q)$. The approximation is piecewise linear Ask L. Rossman to confirm. For any relative pump speed s, $\eta = \eta(q/s)$. Ask Bogumil to confirm.

2.4 Energy and cost calculation in OWA EPANET

Energy consumption of the pump is calculated by integrating the calculated power. Ask L. Rossman how EPANET calculates power from the pump curve and the efficiency curve/efficiency constant. The cost of running the pump is then calculated by multiplying the energy consumed by the unit cost of energy. The unit cost can be specified in three different ways:

- As global unit cost value for the project, in absence of information provided for the particular pump. The global value is supplied within the project's Energy options.
- As average (nominal) energy price per kW-hr supplied for the pump.
- As a time pattern describing the variation (as a series of multipliers) in energy price throughout the day. Each multiplier in the pattern is applied to the pump's Energy Price to determine a time-of-day pricing for the corresponding period. The pump is provided a ID label of the corresponding time pattern.

3 Calculation of power input to a group of parallel identical variable speed pumps operating at equal speeds

The new equations are proposed in [1] to enable the mechanical (and later total, using wire-to-water efficiency) power input calculation for not just a single pump, but for a group of parallel identical pumps which can be fixed or variable speed.

Two alternative models are considered:

Model 1 The mechanical power is approximated directly by a cubic polynomial and scaled by pump speed and number of pumps.

Model 2 The power characteristic is evaluated from hydraulic and efficiency curves - similar to what is done in OWA-EPANET, but now for not just a single pump but for a group of pumps. Ask L. Rossman for comments

The second approach is used if the power data points are not available. Otherwise, the first approach can lead to a more accurate representation. The input data usually provided for a pump is given in the next section.

3.1 Input data (pump characteristics)

If full information about the pump's characteristic is provided to the user, one should expect tabular data like the one shown below. This data can then be approximated with smooth curves.

Flow q	Head h	Efficiency η_p	Power P
q_1	h_1	$\eta_{p,1}$	P_1
$\vdots$	$\vdots$	$\vdots$	$\vdots$
q_n	h_n	$\eta_{p,n}$	P_n

Hydraulic characteristics (for a single pump) can be approximated by a power law (as in OWA-EPANET in case of a three-point curve) or by a quadratic polynomial. The efficiency characteristics are best to be approximated by a cubic polynomial. The power curve is also best to be approximated by a cubic polynomial, according to [1].

Often, some or most of the data is not available. In case (mechanical) power input is not available, it needs to be approximated from head and efficiency curves. If efficiency points are not given, one should often expect to obtain a single peak efficiency point (q^*, η_p^*) where q^* is a peak efficiency flow and η_p^* is the peak efficiency of the pump. In that case $\eta_p(q)$ can be approximated with a cubic polynomial passing through three points: $(0, 0)$, (q^*, η_p^*), and $(\tilde{q}.0)$, where $\tilde{q}$ is the maximum pump flow for which the head increase across the pump is equal to zero. Derivation of the cubic polynomial parameters from q^*, η_p^*, and $\tilde{q}$ is explained in [1].

3.2 Calculation method

In case data points for (mechanical) power input are provided for the pump, then **Model** 1 given in Section 3 is suggested for the direct calculation of energy consumption and the cost of pumping of a pump or a group of pumps. In case the power input data points are not available, the mechanical power input need to be calculated from the hydraulic and the efficiency characteristics of the pump, i.e. **Model 2** needs to be used.

3.2.1 Model 1 - direct mechanical power approximation

Mechanical power data point often form an 'S-shaped' pattern which can be approximated with a cubic polynomial. For a single pump:

$$P(q) = e\, q^3 + f\, q^2 + g\, q + h \tag{4}$$

For a group of pumps:

$$P(q, n, s) = ns^3 P(q/ns) = n\, s^3 \left[e\, q^3 + f\, q^2 + g\, q + h\right] \tag{5}$$

3.2.2 Model 2 - indirect method from hydraulic and efficiency curves

For hydraulic characteristics, find an approximation curve and scale it for a given relative pump speed s and number of pumps in the pump group n. For power law:

$$\Delta h/s^2 = A - B\,(q/ns)^C \tag{6}$$

For a quadratic polynomial approximation:

$$\Delta h/s^2 = A(q/ns)^2 + B(q/ns) + C \tag{7}$$

where (for both approximations) A,B,C are approximation coefficients. The scaling with respect to the number of pumps and the speed is consistent with the affinity laws described, for example in [3].

Find the pump group efficiency it probably needs to be wire-to-water efficiency to be compatible with EPANET $\eta(q, n, s)$. If (η, q) points are available for the pump, then a cubic approximation can be performed to yield the cubic polynomial $\eta(q) = a\, q^3 + b\, q^2 + c\, q$ (with coefficient $d = 0$). In case η^*, q^*, and $\tilde{q}$ are provided then the cubic approximation, according to [1] is given as:

$$\eta(q) = \eta^* \frac{(\tilde{q} - q^*)^2}{(q^*)^2} \left[(\tilde{q} - 2\, q^*)\, q^3 + \left(3q^{*2} - \tilde{q}^2\right)\, q^2 + \left(2\tilde{q}^2 q^* - 3q^{*2}\tilde{q}\right)\, q\right] \tag{8}$$

and is valid under condition: $q^* < (2/3)\,\tilde{q}$

For a group of identical n pumps operating at relative speeds s, $\eta(q, n, s) = \eta(q/ns)$, i.e. $\eta(q, n, s)$ is calculated from Eq. 8 by assigning $q \to q/ns$.

The wire-to-water efficiency η is a product of the efficiency of the converter η_c, the efficiency of the motor η_m, and the mechanical efficiency of the pump η_p.

$$\eta = \eta_c \, \eta_m \, \eta_p \tag{9}$$

$\eta_c \approx 95-95\%$ for higher speeds s and can be significantly lower for low s. η_m is a function of its output power. If the motor is operating above 50% of its output power than $\eta_m \approx \mathrm{const} = 89\%$.

3.2.3 Input power characteristics from hydraulic and efficiency characteristics

For a group of n identical pumps at speed s,input power is then evaluated from the hydraulic power of water and the wire-to-water efficiency

$$P(q, n, s) = 2.725 \times 10^{-3} \, q \, \Delta h(q, n, s)/\eta(q, n, s) \tag{10}$$

where P = mechanical power input to a pump group kW; q = flow rate of a pump group m^3/h, h = head increase in meters given by either a quadratic or power law approximation, and η is the pump wire-to-water efficiency in per unit values.

The electric motor efficiency characteristics depend on output power P, $\eta_m = \eta_m(P)$. $\eta_m(P)$ is usually constant above 50% of pump's rated load and in this case, it can be assumed that $\eta_m = \mathrm{const}$. If higher accuracy is required the motor efficiency characteristic can be interpolated in the working range (above 50% of its rated load) by an analytical function, $\eta_m = \bar{\eta}_m(P)$. In the working range the efficiency characteristic is a regular concave function and can be accurately interpolated, for instance by a quadratic function.

4 Outline of the required work split into individual tasks and the required time per task

The total time for the job estimated by DMU is 300 hrs. The workload has been split (by the author) into the following tasks.

5 Code outline in Program Design Language

The proposed structure of the new algorithm to be added to OWA EPANET in program design language (PDL) [4] is provided below. The algorithm is designed to calculate power input to the group of n equal pumps operating at the same speed s equal ($s = 1$) or different ($s \neq 1$) relative to the nominal speed of the pump for which the hydraulic, efficiency, and power input curves have been obtained. The code outline is listed below:

```
1  Choose the P (mechanical power input) calculation method.
      SELECT (1) direct calculation of mechanical power input from
       the provided power curve approximation and (2) indirect
      calculation of mechanical power input from the hydraulic
      curve and the efficiency curve or efficiency curve
      characteristic points (q_star,eta_star,eta_tilde).
2  INFORM the user that direct method (1) is preferred as it gives
       more accurate predictions.
```

No.	Task	Time (hrs)
1	Familiarization with the calculation method described in [1]	16
2	Familiarization with OWA/EPANET	16
3	Familiarization with C language, Doxygen, GIT, GitHub, CMake	16
4	Preparation of program specification and code description in pseudo-code	24
5	Communication with the software community and devising the best approach to adding the new (proposed) functionality to the existing code	12
6	Writing necessary C code and linking it with the existing software	50
7	Debugging	50
8	Preparing scenarios for testing the performance of the upgraded software	30
9	Updating software documentation in Doxygen	10
10	Running the upgraded code with new and old functionality and comparison of the results	30
11	Merging the upgraded fork with the development branch of OWA-EPANET	30
12	Preparation of the final report	16
	TOTAL:	300

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3 INPUT the user data required in both methods: q (flow for the
     group of pumps), n (number of pumps operating), s (relative
     pump speed), eta_c (converter efficiency), eta_m (motor
     efficiency). eta_m can be a constant or EN_MOTOR_EFFIC_CURVE
      (quadratic approximation curve describing electrical motor
     efficiency vs. mechanical input power P(q,n,s))
4 INFORM the user that if P > 0.5 P_rated, i.e. above 50% of the
     rated power then eta_m is approx. constant. Otherwise, it is
      adviseable that eta_m is approximated by
     EN_MOTOR_EFFIC_CURVE.
5 IF direct calculation INPUT EN_POWER_CURVE; CALCULATE P(q/ns)
     for given q,n,s using EN_POWER_CURVE. Then CALCULATE the
     mechanical input power of the pump group P(q,n,s) = n*s^3*P(
     q/ns)
6 IF indirect calculation INPUT EN_PUMP_CURVE or
     EN_PUMP_CURVE_QUAD and EN_EFFIC_CURVE or a vector (q_star,
     eta_star,eta_tilde). EN_PUMP_CURVE is the EPANET's pump's
     head vs flow curve using power law approximation.
     EN_PUMP_CURVE_QUAD is the new (added) curve for pump's head
     vs flow using quadratic approximation. EN_EFFIC_CURVE is
     EPANET's approximation curve for pump's mechanical
     efficiency vs. flow. (q_star,eta_star,eta_tilde) are,
     respectively: peak efficiency flow, peak efficiecy, and cut-
     off flow.
7 For a given q,n,s CALCULATE delta_h(q,n,s) = s^2 * delta_h(q/ns
     ) calculated from EN_PUMP_CURVE or EN_PUMP_CURVE_QUAD. Then
     CALCULATE eta(q/ns) from EN_EFFIC_CURVE or analytically from
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     cubic approximation with coefficients (a,b,c,d) obtained
    from (q_star,eta_star,eta_tilde) using equations from
    Ulanicki et al. CALCULATE eta(q,n,s) = eta(q/ns).
For a given q,n,s CALCULATE P(q,n,s) = 2.725 * 10^-3 * q *
    delta_h(q,n,s)/eta(q,n,s)
For both (direct or indirect) methods, CALCULATE Ptot(q,n,s) =
    P(q,n,s)/(eta_m * eta_c) where eta_m is constant or is
    calculated from EN_MOTOR_EFFIC_CURVE.
```

References

[1] B. Ulanicki, J. Kahler, and B. Coulbeck, "Modeling the Efficiency and Power Characteristics of a Pump Group," *Journal of Water Resources Planning and Management*, vol. 134, no. 1, pp. 88–93, February 2008.

[2] L. A. Rossman, *EPANET 2 USERS MANUAL*, United States Environment Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH 45268, September 2000.

[3] T. Walski, B. T.E., E. Harold, L. B. Merritt, N. Walker, and B. E. Whitman, *Wastewater collection system modeling and design*. Haestad Press, 2004.

[4] S. McConnell, *Code Complete, Second Edition*. USA: Microsoft Press, 2004.