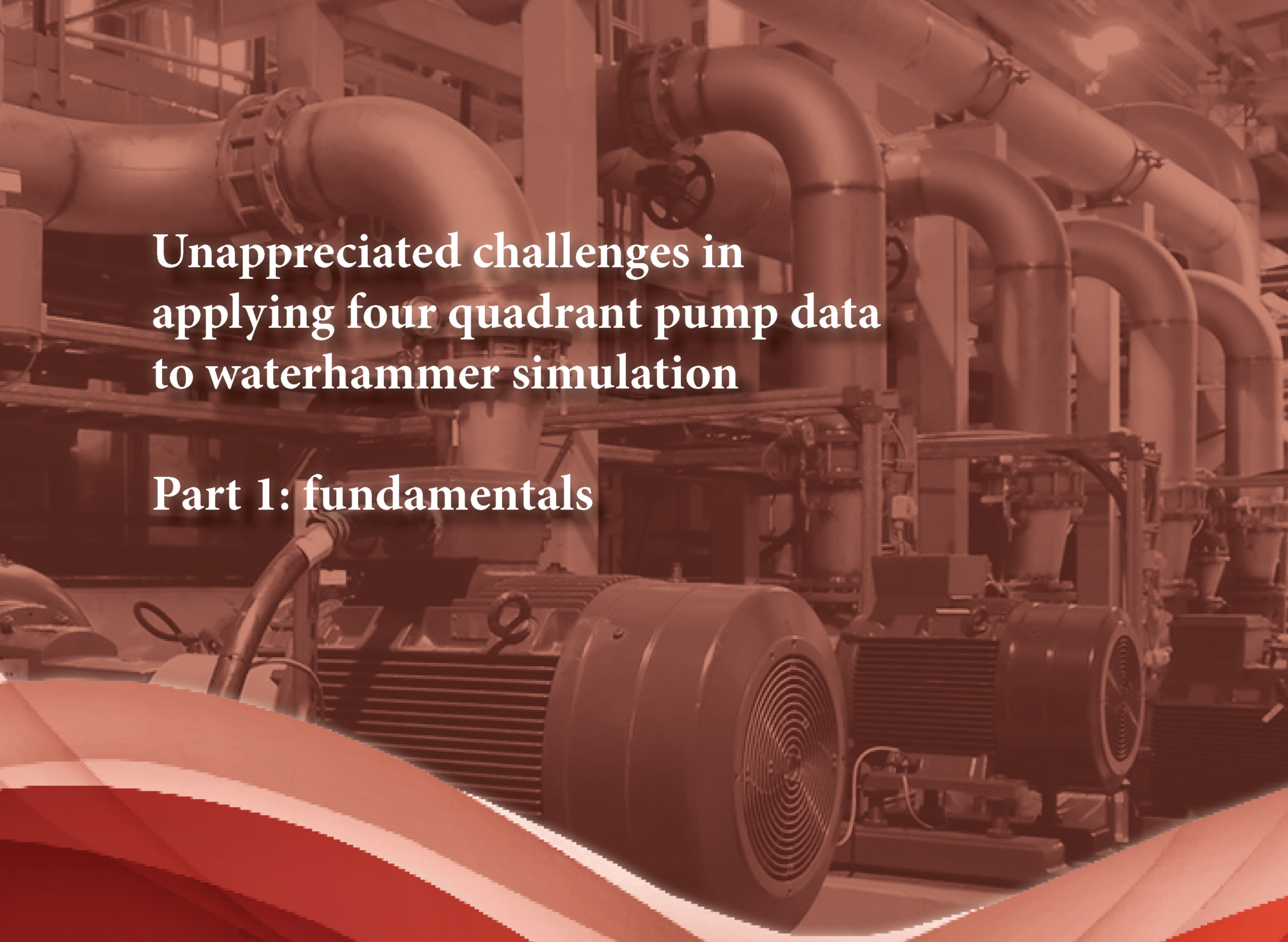

Unappreciated challenges in applying four quadrant pump data to waterhammer simulation

Part 1: fundamentals

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Unappreciated challenges in applying four quadrant pump data to waterhammer simulation part 1: fundamentals

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ABSTRACT

The transient analysis of reverse flow and rotation in pumps has evolved over the years into modern four quadrant pump waterhammer simulation. Exact characteristics for a given pump for reverse flow and/or reverse rotation are normally unavailable, and manufacturer curves are often mapped to previously published four quadrant data sets for similar pumps. Assumptions made in this mapping process can cause extreme differences in the simulation. If these assumptions are unaddressed, critically incorrect conclusions about the system's transient behavior may be made, impacting both design and operation. The available choices to the waterhammer analyst and the consequences of those choices are thoroughly detailed in Part 1 of this paper.

NOMENCLATURE

BEP	Best Efficiency Point (rated conditions for pump)
MC	Manufacturer curve for a pump
Ns	Specific speed of pump (dimensionless/Metric/US units)
OP	Operating point for a steady-state
4QBEP	4QDC created by reference to the BEP
4QDC	Four quadrant dimensionalized curve for a pump
4QOP	4QDC created by reference to the OP

<u>Suter dimensionless parameters for four quadrant pump representation</u>

h	dimensionless head (pump operating head divided by the rated head)
α	dimensionless speed (pump operating speed divided by the rated speed)
β	dimensionless torque (pump operating torque divided by the rated torque)
v	dimensionless flow (pump operating flow divided by the rated flow)
F_H	$h / (\alpha^2 + v^2)$
F_B	$\beta / (\alpha^2 + v^2)$
θ	$\tan^{-1}(\alpha / v)$

1 INTRODUCTION

Some systems involve reverse flow through pumps during transient events. If sustained this can lead to reverse rotation. Predicting centrifugal (rotodynamic) pump hydraulic behavior and system response during transient events is critical to ensure safe design and operation. This impacts pipe pressure design, design of pipe structural supports, sizing and location of surge mitigation equipment, and guidelines provided to operators.

Configurations susceptible to reverse flow through pumps fall into two basic categories:

- Parallel pump operation where pumps trip and at least one remains running
- Pumping to a higher elevation or pressure (e.g., a rising main)

The standard method to prevent reverse flow is the use of check valves – usually at the pump discharge. Systems with check valves can have short-term, reverse pump flow before the check valve fully closes (e.g., see Lozano, Bosch and Walters, 2018 (1)). Some pumping systems do not or cannot use check valves, including pumping of slurries and large condenser cooling water systems. Moreover, some pump systems are purposely designed to have reverse flow through the pump such that the pump can run in "turbine mode" and be used to generate power (Binama et al., 2017, (2)). Systems without check valves often have power operated valves that may or may not close during a pump trip event, depending on the design.

Predicting pump behavior under reverse flow and potentially reverse rotation is a complicated task even with good data for a given pump. But good (or any) data is rarely available for reverse flow or rotation. Pump manufacturers perform rigorous testing of their pumps and publish performance data for head, power and efficiency in the zone of normal pump operation – forward flow and positive rotation. Testing is rarely performed in the zones of reverse flow or rotation.

It was recognized as far back as the 1930's that understanding reverse flow and rotation of pumps was going to be an important part of future engineering efforts – especially in large water works projects under consideration at the time. Important first steps in this direction were made by Kittredge and Thoma, 1931 (3) and Knapp, 1937 (4). Progress in the ensuing decades culminated in the publications of Marschal, Flesch and Suter, 1965 (5) and Suter, 1966 (6). What emerged from these two publications is what we know today as the "Suter Method" of organizing four quadrant pump data into a dimensionless form convenient for digital simulation.

To most in the waterhammer community, this is a settled issue of engineering practice. However, it appears to the authors that serious challenges remain which have not gained the appreciation they deserve. Specifically, four quadrant data are made dimensionless relative to the best efficiency point (BEP) of the pump. This is also known as the rated operating point of the pump and, as such, will often include a subscript "R" on hydraulic data at the BEP/rated point. The term "rated" is an ambiguous term for pumps as noted by Brown, 1968 (7), but in the context of four quadrant data, it is equivalent to BEP. In Parts 1 and 2 of this paper, the two terms will be used interchangeably.

In that it is rare to find a pump in the field operating at its BEP, this raises what should be an obvious question. How does one properly correlate and apply four quadrant pump data referenced to BEP to a pump operating away from its BEP? It will be shown that the answer to this question is nowhere near as obvious and clear-cut as most seem to imply. Further, it will be shown in Part 2 of this paper that how one answers this question can have a dramatic effect on waterhammer simulation predictions. Finally, some guidelines for practicing waterhammer engineers will be proposed with the goal of helping ensure conservative predictions are obtained, thereby enhancing safety in design and operations.

2 HISTORICAL DEVELOPMENT OF FOUR QUADRANT DATA

Centrifugal pumps can be loosely placed into three categories:

- Radial flow –The predominant feature is the generation of pressure head by directing a fluid radially outward inside the pump casing. Such pumps are most suited to low flow/high head applications. The pump specific speed Ns is a low value relative to other pumps.
- Axial flow – The predominant feature is the generation of pressure head by directing a fluid axially along a cylindrical casing. Such pumps are most suited to low head/high flow applications and often have multiple axial stages to increase generated head. The pump specific speed Ns is a high value relative to other pumps.
- Mixed flow – The geometry is in between radial and axial flow designs and shares traits of both. The pump specific speed Ns is an intermediate value relative to other pumps.

As summarized in the previous section, ground-breaking research into the behavior of centrifugal pumps undergoing reverse flow and/or rotation was undertaken in the 1930's by Kittredge and Thoma, 1931 (3) and Knapp, 1937 (4), which was focused on radial flow pumps. Evolving from Knapp's research at Caltech was the work by Swanson, 1953 (8), who published data on mixed and axial flow pumps. Swanson's specific goal was to provide four quadrant data for each type of pump geometry so that engineers had a more complete picture on how pumps operate in the four quadrants.

While highly valuable, Swanson's data was only given for lines of constant dimensionless head and torque at 100%, 0% and -100% of rated values in the dimensionless flow vs. speed plane. Donsky (9) obtained Swanson's data (8) from A. Hollander and, using pump similarity laws (more commonly called "affinity" laws in the context of pumps), developed these into full sets of four quadrant data. Donsky's curves were still dimensionless, but converted into the more familiar (to practicing engineers) flow vs. head plane. Further, Donsky's curves were more tightly spaced at roughly 10% increments and taken to roughly 200% of rated conditions. The Donsky curves are familiar to every waterhammer engineer who works with pumps.

A note of caution on the Donsky curves is in order. It is well known that the affinity laws are good approximations of predicting pump performance based on speed changes when the flow, head and speed are all positive values. The validity of the affinity laws when any of the head, flow and/or speed are negative is not clear to the authors.

Popular textbooks have pushed four quadrant data methodology and the Knapp/Swanson/Donsky curves into the mainstream of waterhammer application. For example, see Wylie and Streeter, 1993 (10), Swaffield and Boldy, 1993 (11), Thorley, 2004 (12), and Chaudhry, 2014 (13). Donsky is usually the one given credit for these three curves and this paper, Parts 1 and 2, will follow suit and reference Donsky. All modern textbooks present the Donsky curves in the now standard Suter Method form (5, 6) discussed in the previous section.

One of the first published four quadrant pump field studies to include friction was by Brown, 1968 (7), a colleague of Donsky at the US Bureau of Reclamation. Brown's study also included water column separation and used Donsky's four quadrant data for a radial flow pump in the waterhammer simulation. Brown's field study helped to firmly entrench the idea that one can take a pump's specific speed, identify four quadrant data from a different pump but of similar specific speed, and use this data in the simulation.

Later, Brown and Rogers, 1980 (14) published several new four quadrant pump data sets from manufacturers and their own field studies. Despite the success using the similar specific speed method in Brown's earlier study, Brown and Rogers questioned the validity of using pump specific speed as a correlating factor for four quadrant pump data. The additional data they collected showed a much weaker correlation between four quadrant characteristics and specific speed for radial flow pumps, while mixed and axial flow pumps showed better correlation.

Recognizing the need for broad availability of pump four quadrant data sets for various specific speeds, Martin, 1983 (15) aggregated references for 26 data sets. Thorley et al., 1996 (16) published curves and numerical data for 14 specific speeds. Recent years have seen additional research and aggregation of four quadrant data sets. Ayder et al., 2009 (17) published seven complete sets of data from their own experiments. Giljen et al., 2016 (18) aggregates nine sets of partial four quadrant data.

It should be noted that some have questioned the use of steady-state, four quadrant pump data to adequately represent transient pump behavior. This certainly goes back to Knapp, 1937 (4). Gros et al., 2011 (19) used experiments and detailed transient numerical (CFD) methods which demonstrated such discrepancies.

3 A REVIEW OF FOUR QUADRANT PUMP METHODOLOGY

3.1 A four quadrant pump curve

Fig. 1 shows four quadrant data for a radial flow pump from Swanson, 1953 (8) obtained from previous work by Knapp, 1937 (4). Swanson made the test data dimensionless with reference to the rated conditions of the test pump at its BEP. It appears the test pump was Knapp's 4-inch pump. The dimensional rated conditions of the pump were not included by Knapp or Swanson.

3.2 Review of Suter Method

In recent decades, four quadrant data is almost always presented in dimensionless form. Head, torque, speed and flow are made dimensionless (h, β, α, v) by dividing their measured values with a reference value. This reference condition is almost always the BEP of the pump which is the rated point, R, as discussed earlier.

To avoid calculations through the zero point, the Suter Method involves transforming the constant head and torque lines in the speed-flow plane to a polar coordinate system via the transformation equations below (11, 13). Note that these definitions vary depending on the reference.

$$F_H = \frac{h}{\alpha^2 + v^2} \quad F_B = \frac{\beta}{\alpha^2 + v^2} \quad \theta = \tan^{-1}\left(\frac{\alpha}{v}\right) \tag{1}$$

Fig. 2 shows the Suter curves as developed from the Donsky, 1961 (9) radial flow pump data. This is the same pump as Fig. 1.

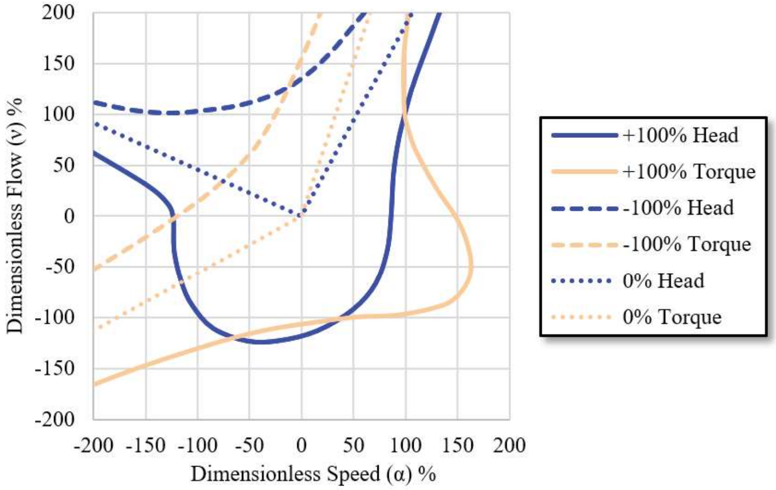

Figure 1. Four quadrant test data from a radial flow pump (4, 8), Ns = 0.46 (24.6 Metric/1270 US).

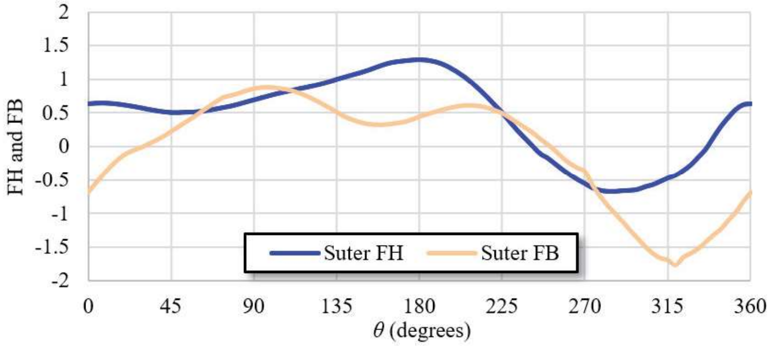

Figure 2. Suter curves constructed from a radial flow pump (4, 8, 9) via Eq. 1. The specific speed for the test pump is Ns = 24.6 Metric (1270 US).

3.3 Pump manufacturer curve

Typical data from a centrifugal pump manufacturer includes a family of dimensional curves for various impeller diameters and, in some cases, various speeds. Fig. 3 shows a real manufacturer curve for a PumpWorks 10x12x21 PWH unit with a 19.5 inch (49.5 cm) impeller diameter at 890 RPM. The specific speed of 24.5 Metric (1266 US) is almost exactly the same as Figs. 1-2.

3.4 Pump operation point away from BEP (rated point)

While a pump is designed to run at its BEP, the installed piping system will dictate where the pump actually operates. This is called the operating point (OP). It is very common to find pumps operating far away from their BEP. For example, see the Reference (20) case study where pumps operated as low as 23% of the BEP at a chemicals plant in the USA. This has many ramifications related to pump reliability and energy efficiency, but here we will focus on how it affects waterhammer simulation.

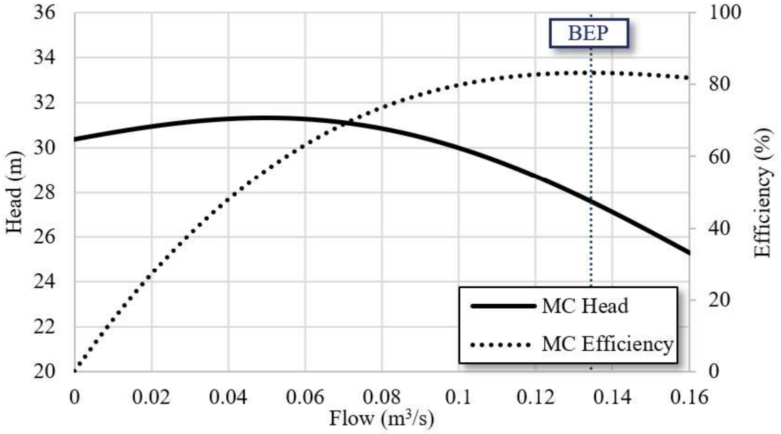

Figure 3. A manufacturer curve with Ns = 24.5 Metric (1266 US), PumpWorks 10x12x21 PWH 19.5 inch (49.5 cm) impeller, 890 RPM.

3.5 Mapping the four quadrant curve to the manufacturer curve

During the collection of four quadrant experimental or field data as in Fig. 1, the pump is operated in all manner of off-BEP conditions. When this data is organized into the Suter Method form (5-6), it is made dimensionless relative to the BEP of the tested pump. When applying this data in waterhammer simulation, at some point the Suter data must be made dimensional again relative to the operating pump. This will involve selecting a reference point. This will be discussed in a later section.

3.6 A note on pump specific speed calculation

As the first author researched this paper, it was not clear if many of the four quadrant data references calculated the pump specific speed correctly. API 610, 2010 (21) and ANSI-HI 1-1-1.2-2014 (22) define how a pump specific speed is calculated. These methods agree with each other and are faithfully represented by Howie, 2017 (23). The first author has two specific areas of concern: 1) Rated flow and head are to be that at the maximum impeller diameter for the pump, and 2) Multi-stage pumps are to use the head for a single stage only and not the total head for the pump. There seems to be a belief going back to Knapp, 1937 (4) and carrying on though most or all subsequent researchers, that specific speed is calculated using the rated operating conditions of the individual pump. It isn't. This topic is outside the scope of this paper but calls for further research and closer attention from those who publish and use four quadrant pump data.

3.7 Defining some terminology

Summarizing the information in Section 3, some terms will be defined.

- Manufacturer Curve (MC)
  - Manufacturer provided data for the pump of interest, at a particular impeller trim and speed. This includes positive head, efficiency, and power over a range of positive flows – the normal pumping zone.
  - Can be adjusted for speed with affinity laws. This allows the determination of the hydraulic behavior for speeds other than the rated speed.
  - Does not contain any information related to reverse flow or rotation.

- Four Quadrant Dimensionalized Curve (4QDC)
    - This curve contains the same parameters as the MC, but the source is a four quadrant data set instead of the manufacturer.
    - Must be dimensionalized with a reference point, such as the BEP or steady-state operating point (OP).
    - Has complete information for both reverse flow and rotation.

3.8 Summary of process for analyzing reverse flow and rotation in a system

An MC is available for a given pump but does not contain information for reverse flow or rotation. For such a simulation, four quadrant data is required. Ideally, this data is available for the pump in question and can be directly applied. However, four quadrant data is rarely available. Instead, specific speed is used to select a suitably *similar* pump that has been tested in all four quadrants.

The four quadrant data from the *similar* pump is then *dimensionalized* to a 4QDC with a reference point related to the pump being studied. This reference point, derived from the *actual* MC, could be very different than the one used with the original pump. With this 4QDC, an estimate for pump behavior at all flows and speeds is obtained.

4 SELECTING A REFERENCE POINT

When performing a waterhammer simulation, typically only an MC is available to characterize a pump. As this lacks the required information for reverse flow and rotation, specific speed is used to select an appropriate existing four quadrant data set. The dimensionless four quadrant data set is then re-dimensionalized with a reference point. The original reference point used to make the data dimensionless was likely the BEP of the test pump. If this exact reference point was used to create a 4QDC, all hydraulic parameters would match the four quadrant test pump exactly.

The pump being analyzed will usually differ from the four quadrant test pump. Even if the pump is running exactly at BEP, and the specific speed matches exactly, the MC and the 4QDC will have a different shape. This is due to differences in the pump design.

What reference point should be chosen when the pump is not running at BEP? What are the consequences of choosing certain reference points? The two most common and straightforward choices are defined later in this section.

4.1 Matching steady-state and transient simulations

Every transient waterhammer simulation requires initial conditions, as determined from a steady-state simulation. The physical parameters of the system cannot change between the steady-state solution and the transient solution without causing artificial disruption to the calculation. Therefore, the same pump operating point must be used in both the steady-state and transient simulations. If a transient simulation may involve reverse flow and rotation in the pump, the transient simulation requires four quadrant data – the 4QDC. To avoid the artificial disruption to the calculation, the steady-state simulation must use the same 4QDC as used in the transient.

4.2 Using BEP as the reference point – the 4QBEP

The most straightforward way to create the 4QDC is to use the BEP determined from the MC. As the original four quadrant data was likely created based on the BEP of the test pump, it would seem appropriate to use a similar reference to re-dimensionalize the data. This will be called the 4QBEP.

The real pump introduced in Fig. 3 has a specific speed almost exactly the same as the test pump described by Fig. 1 from Swanson (8) and Knapp (4). As described previously, Donsky (9) expanded the Swanson data and later it was organized in Suter form as shown in Fig. 2. When the Fig. 3 pump is compared to the Fig. 2 four quadrant data using the BEP from Fig. 3, Fig. 4 shows how the curves differ.

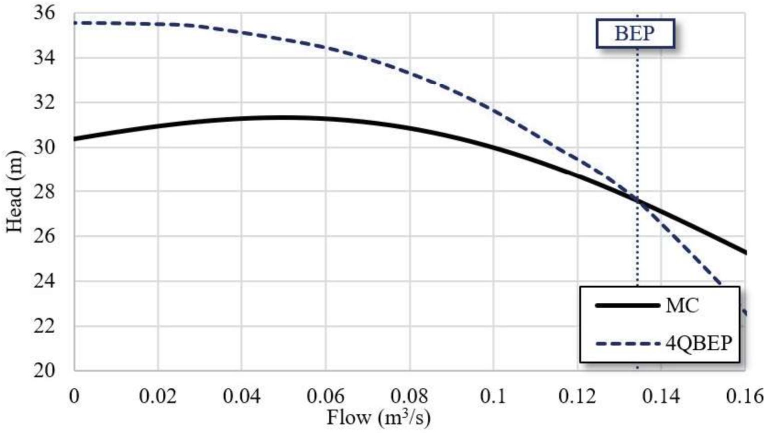

Figure 4. Dimensionalizing existing four quadrant data (Figs. 1-2) using the BEP of the pump described by Fig. 3.

The fact that the 4QBEP data is representing a *similar* pump, rather than the pump defined by the MC, has direct implications on the simulation. Most prominently, the steady-state solution will not agree with the MC except by chance. This is true for steady-state solutions anywhere on the 4QBEP, except exactly at BEP.

Fig. 5 shows the steady-state operating points determined using the MC and the 4QBEP and the system curve. These are determined using a steady-state analysis of the system using the MC and 4QBEP pump curves. The MC curve is the real pump curve for the system, hence the OP determined by the MC is the real OP. The OP determined by the 4QBEP is an artifact of imperfect matching of the Figs. 1-2 data to the BEP of the MC. Depending on how well the 4QBEP and MC happen to agree, this effect could be significant, and is often amplified the farther away from BEP the pump is operating.

4.3 Using the steady-state operating point as the reference point – the 4QOP

To overcome the issue of a mismatched initial steady-state result (between the MC and 4QBEP, as discussed in previous section), another pragmatic and convenient option is to use the actual initial operating point (determined using the MC) as the reference point in creating the 4QDC. This will force the initial steady-state results to match the MC exactly. This will be called the 4QOP curve. The 4QOP uses the same data as the 4QBEP, but the reference point has been changed to the OP. See Fig. 6.

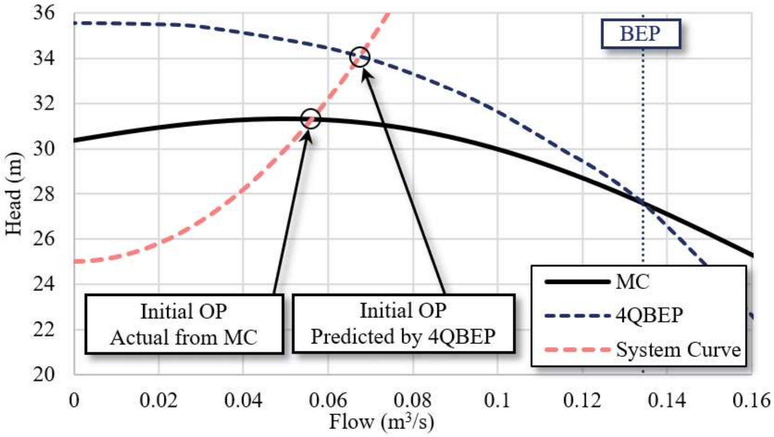

Figure 5. Steady-state mismatch between 4QBEP and MC. The actual OP for the given system is dictated by the MC, but the 4QBEP prediction differs.

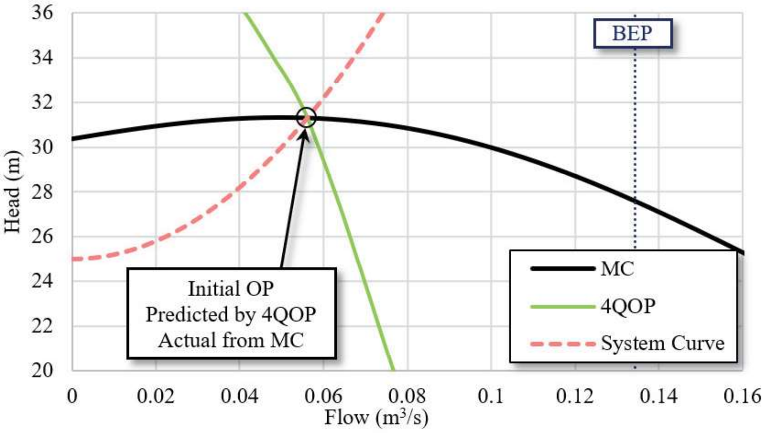

Figure 6. Dimensionalizing the existing four quadrant data (Figs. 1-2) using the actual OP of the pump based on the same system curve shown in Fig. 5.

It should be noted that the 4QOP and MC still only exactly match at one point. Instead of matching at BEP, they are now matched at the OP. At all other points on the 4QOP, steady-state solutions will vary from the MC except by good fortune. This becomes important when analyzing a final steady-state value after a waterhammer transient has died out. Two different final operating points are predicted – one for the MC (the actual final operating point), and one for the 4QOP. See Fig. 7.

When operating far from BEP, the 4QOP method tends to cause greater distortion to the 4QDC. This can potentially cause a sense of false security – the curve can be very different than the MC, but display accurate initial steady-state results, which are the most intuitive to check.

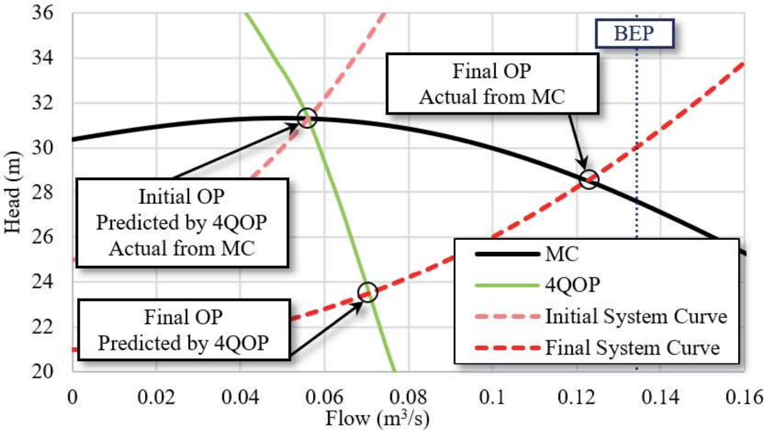

Figure 7. The 4QOP curve only matches the MC at the Initial OP. Changing system behavior to the Final System Curve during the transient causes an OP mismatch (the Final System Curve results after all transients have died out).

4.3.1 Identifying the reference point values for use in the 4QOP method

The 4QOP method requires knowledge of the initial steady-state conditions. These initial conditions can only be determined by running a steady-state simulation with the MC.

By definition, the 4QOP and the MC intersect at the initial steady-state OP. This means the initial conditions for the transient solution can be determined directly with the MC, with the 4QOP only being used in the transient solution. Both curves can be used without artificial disruption in the transient calculations.

Further, if the waterhammer simulation considers multiple initial operating condition scenarios, the 4QOP will change for each initial OP. On the other hand, since the 4QBEP is anchored to the BEP, which does not change, the same 4QBEP curve will be used for all initial operating condition scenarios.

5 MC TRANSIENT TORQUE BALANCE AS A THIRD OPTION FOR FIRST QUADRANT MODELING

It should be mentioned that engineers can also use the MC during the transient simulation with a torque balance model and affinity laws. See Chaudhry, 2014 (13), pp. 125-126 for the standard torque balance, and Applied Flow Technology, 2016 (24) for coupling torque balance with affinity laws. With MC power data vs. flow rate (always available from a manufacture for positive flow at a given positive speed), one can easily determine torque for a given rotational speed. This method is more accurate than four quadrant methods in the first quadrant but cannot be used for negative flow, speed or head. However, it can be used to check the 4QBEP and 4QOP results while still in the first quadrant (positive flow, speed and head).

6 CONSEQUENCES OF REFERENCE POINT SELECTION

The selection of either the 4QOP or 4QBEP method can have a substantial effect on the results of both steady-state and transient simulations. It is evident that differences in steady-state results should be expected with either method. While the 4QOP option forces accurate initial steady results (Fig. 6), final steady-state results after a transient event has died out are likely to be incorrect (Fig 7). The 4QBEP is usually incorrect for the initial steady-state (Fig. 5) as well as the final steady-state (not shown).

Transient results are more difficult to conceptualize. It is reasonable to state that, because the operating curves are different, some transient differences may be expected. What appear to be minor differences in the 4QDC options can, perhaps unintuitively, be the cause of significant differences in a transient simulation.

For example, if a valve is known to close at a certain time, the 4QBEP option may predict significant flow through the valve as it closes, causing subatmospheric pressure conditions or even significant cavitation, whereas the 4QOP option may predict a much lower flow through the valve, avoiding subatmospheric conditions and cavitation. One can see how this could easily result in an engineer recommending surge suppression equipment and devices that are not required, or, worse, not recommending surge suppression when it is in fact needed. The authors have developed example cases showing such effects and the differences between the 4QBEP and 4QOP options, as presented in Part 2 of this paper. Table 1 summarizes the key differences between the 4QBEP and 4QOP. Note that MC transient torque balance method (Section 5) is always accurate for all Table 1 conditions until flow, head or speed become negative.

Table 1. Comparison of the 4QBEP and 4QOP reference points

Method	4QBEP	4QOP
Calculations needed to determine	None, only pump BEP needed	Full steady-state calculation needed to determine OP
Steady-state pump and system model	MC ignored except for BEP, steady-state conditions calculated using 4QBEP curve	MC used to calculate steady-state OP, no four quadrant data needed
Transient pump model	Pump follows four quadrant behavior referenced to BEP	Pump follows four quadrant behavior referenced to OP
Initial Suter values	Depends on steady-state as determined by 4QBEP, but both F_H and F_B fall along original Suter curve values	F_H and F_B equal 0.5 by definition
Correctness of initial steady-state	Incorrect except by good fortune	Correct
Correctness of final steady- state	Incorrect except by good fortune	Incorrect except by good fortune
Pump curve consistency across different initial operating cases	Consistent, the transient pump curve does not depend on operating case	Not consistent – each system operating scenario (where the steady-state flow rate changes) will have a different OP and thus use a different 4QOP transient pump curve

Further, note that any waterhammer software which does not have a built-in steady-state solver and relies on running the transient solver for some duration to determine the steady-state (before starting the transient calculation) is using 4QBEP. Use of 4QOP is only possible if the waterhammer software has a built-in steady-state solver or allows users to import or define their own steady-state, initial conditions.

7 RECOMMENDATIONS

Wan and Huang, 2011 (24) provide an alternative to the 4QBEP and 4QOP options discussed in Section 4. What they essentially do is keep the four quadrant curve of interest but modify it using the manufacturers curve in the first quadrant zone of normal pump operation. This avoids the issues raised in this paper but ends up with a four quadrant curve no longer consistent with the original test data. There also is a significant discontinuity at zero flow in their proposed method. It is not clear to the authors whether this offers any substantial improvement. Wan and Huang should be applauded for recognizing that an issue exists.

For the practicing engineer, the authors have no recourse but to recommend substantial sensitivity studies be performed in waterhammer simulations. Both 4QBEP and 4QOP should be evaluated. Comparisons should be made to MC transient results in the first quadrant (see Section 5). Multiple four quadrant data sets near the pump specific speed of interest should be included. Engineers should identify the initial and final steady-states of the system and consider transient simulation results in light of agreement with the final steady-state results after all transients have died out.

8 CONCLUSION

Significant and potentially dangerous differences exist in waterhammer simulation results based on two different applications of four quadrant methods. These differences result from certain steady-state and transient assumptions about a pump’s behavior. Engineers are highly encouraged to expand the scope of their sensitivity studies to account for these differences.

9 ACKNOWLEDGMENTS

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