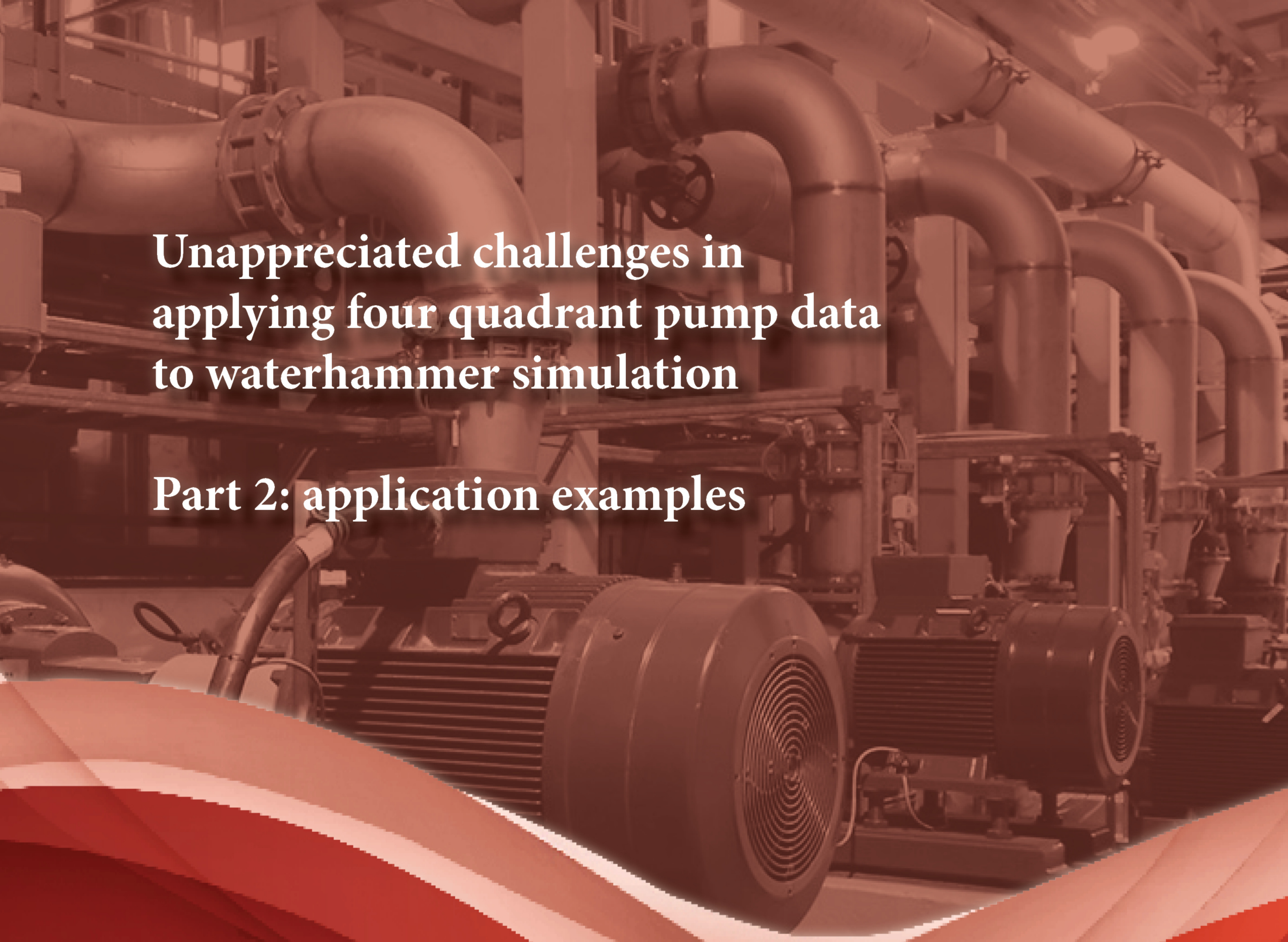

Unappreciated challenges in applying four quadrant pump data to waterhammer simulation

Part 2: application examples

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Unappreciated challenges in applying four quadrant pump data to waterhammer simulation part 2: application examples

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ABSTRACT

Transient analysis of reverse flow and rotation in pumps requires the use of four quadrant data. This data is normally unavailable for a given pump, and existing dimensionless four quadrant data is selected based on specific speed. There are different methods for dimensionalizing the four quadrant data, which can result in significant differences in transient predictions. This study examines four examples with three exhibiting reverse flow. The two most convenient methods of dimensionalizing four quadrant data are used, and significant differences in transient predictions are demonstrated and discussed.

NOMENCLATURE

BEP	Best Efficiency Point of a pump
ESD	Emergency Shutdown Valve (motor operated)
MC	Manufacturer curve for a pump
MOC	Method of Characteristics
Ns	Specific speed of pump (Metric/US units)
OP	Operating point for a steady-state
4QBEP	4QDC created by reference to the BEP
4QDC	Four quadrant dimensionalized curve
4QOP	4QDC created by reference to the OP

1 INTRODUCTION

As described in detail in Part 1 (1), existing four quadrant data is often used to analyze reverse flow and rotation in pumps when no test data for that pump is available. A four quadrant data set that represents a suitably similar pump is selected based on specific speed, under the assumption that the similar pump will exhibit similar transient characteristics.

Creating the 4QDC requires a reference point to re-dimensionalize the four quadrant data. There are two convenient and pragmatic choices as detailed in Part 1:

- The Best Efficiency Point (BEP), creating a 4QBEP curve
- The steady-state operating point (OP), creating a 4QOP curve

Because the two reference points are not likely to be the same, the choice of reference point has significant implications for both steady-state and transient simulations.

Additionally, it is not always clear what existing four quadrant data set should be used. While using one of similar specific speed to the MC is advisable and most common, there are many from which to choose. Differences in individual pumps means that even a data set with matching specific speed may not be the best choice. The effects of varying four quadrant data sets are explored.

Due to this difference in applied characteristics, transient simulations can be dramatically impacted. The two 4QDC methods seem to diverge in their predictions the farther from BEP the pump is operating. It is very common to find pumps operating far away from their BEP as discussed in Part 1. This has many ramifications related to pump reliability and inefficient use of energy, but here we have developed and analyzed practical examples to demonstrate how it affects waterhammer simulation.

2 TRANSIENT METHODOLOGY AND FOUR QUADRANT DATA SETS

The examples in this paper use the commercially available AFT Impulse software, 2016 (2). It uses the Method of Characteristics (MOC, e.g. see Wylie and Streeter, 1993 (3)) and has a built-in steady-state solver to initialize the MOC.

Several reputable and frequently cited four quadrant data sets were compared:

1. **Ns = 22.1 Metric (1140 US) (0.42 dimensionless)**
   From Brown and Rogers, 1980 (4), aggregated in Martin, 1983 (5)
2. **Ns = 24.6 Metric (1270 US) (0.46 dimensionless)**
   From Donsky, 1961 (6)
3. **Ns = 41.9 Metric (2160 US) (0.79 dimensionless)**
   From Thorley, 1996 (7) – also in 2004 (8)

3 PARAMETERS COMMON TO ALL EXAMPLES

All examples pump water with a Grundfos 1220-A/B KP double suction, horizontal split case pump operating at 893 RPM with a 472 mm impeller trim – see Reference (9). The Manufacturer Curve (MC) is shown in Fig. 1. The data sheet for this service condition is available from the authors. The head and power curves are represented by third-order polynomial curve fits, shown below with rounded constants.

$$\Delta H = 28.9 + 14.8Q - 73.3Q^2 + 2.17Q^3 \quad (1)$$

$$P = 51.5 + 135.5Q + 25.5Q^2 - 165Q^3 \quad (2)$$

where ΔH is head rise (m), P is power (kW) and Q is volumetric flow rate (m^3/s). Correlations to power developed by Thorley (8) give a total rotating inertia estimate of 10 kg-m^2 for this pump. All valves in the examples are ball valves and follow the same head loss coefficient (Cv) vs. time profiles, as shown in Fig. 2.

Tank pressures defined in the example schematics Figs 3 & 15 are absolute pressures at the inlet of the connected pipe. Liquid height and Tank outlet pressure remain constant throughout the transient simulation. The high pressures noted would not be unusual for a system with pressurized tanks.

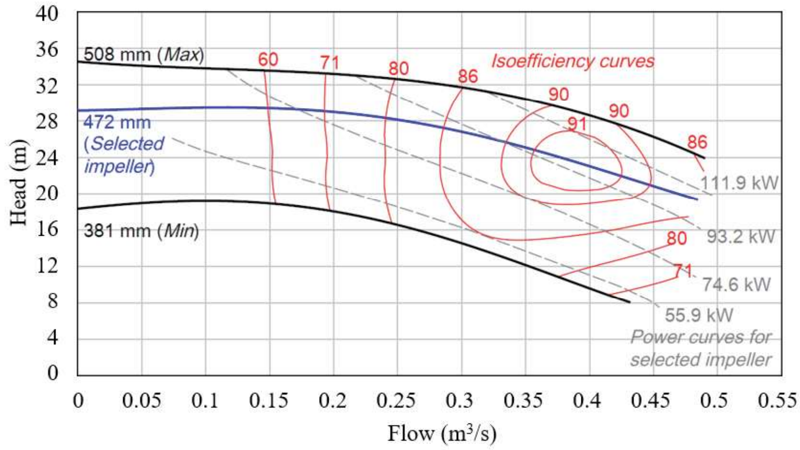


Figure 1. Manufacturer curve (MC): BEP = 0.39 m^3/s, rated head = 23.0 m, Best Efficiency = 91.5%, Ns = 32.0 metric (1653 US)

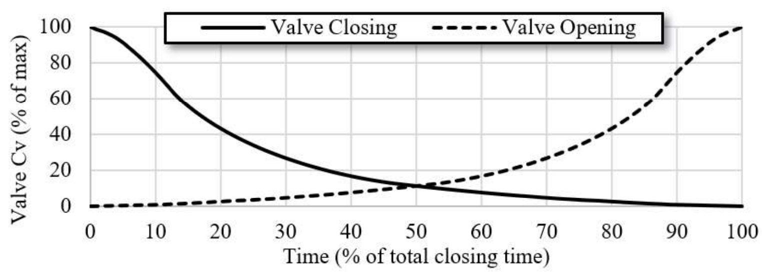


Figure 2. Opening and closing profiles for a typical linearly actuated ball valve

4 EXAMPLE 1 – PUMP TRIP WITH ESD CLOSURE

4.1 System configuration and transient data

The example 1 system is shown in Fig. 3 with required hydraulic information noted. Valve B remains closed throughout the simulation. The pump trips at time zero. There is no check valve in this system. The ESD, a motor operated ball valve, also begins closing at time zero to prevent sustained reverse flow. The ESD follows the characteristic in Fig. 2, closing over 2.5 seconds.

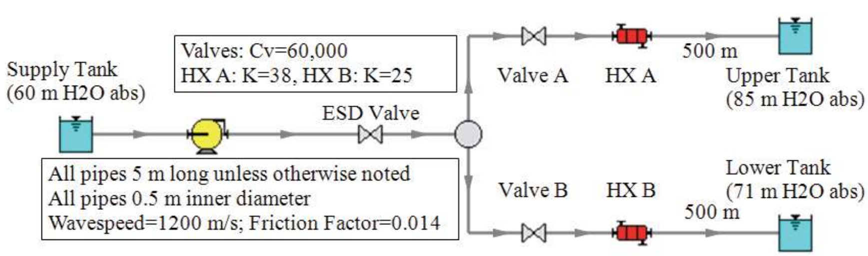


Figure 3. Example 1 schematic

4.2 Initial steady-state behavior

It is not common in waterhammer studies to see pump vs. system curves. In this study they are a very helpful construct to understand not only the behavior of the system but also the effects of using the MC and both the 4QBEP and 4QOP.

4QBEP curves can be created without knowledge of the system, and such curves for each specific speed (see Section 2) are shown in Fig. 4. Note in Fig. 4 that the Ns = 24.6 Metric (1270 US) curve follows the MC quite closely. This is happenstance. One can see for a different manufacturer curve in Part 1, Fig. 4, how this same four quadrant data set is quite different from the MC.

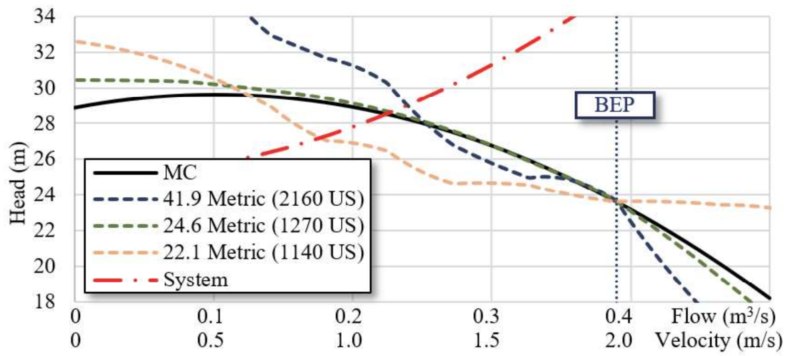


Figure 4. MC and 4QBEP for each four quadrant data set

Table 1 shows the steady-state conditions determined using the Fig. 4 pump curves. Note how the Ns = 22.1 Metric (1140 US) case predicted flow rate of 0.177 m^3/s is far below the MC prediction of 0.224 m^3/s.

Table 1. Pump steady-state results for the 4QBEP curves and MC. The BEP for all cases is 0.39 m^3/s

	Ns	Flow (m^3/s)	Vel. (m/s)	Head (m)	% of BEP
MC	32 Metric (1653 US)	0.224	1.14	28.5	57.6
4QBEP	22.1 Metric (1140 US)	0.177	0.90	27.2	45.4
	24.6 Metric (1270 US)	0.227	1.16	28.6	58.4
	41.9 Metric (2160 US)	0.239	1.22	29.0	61.4

The actual pump conditions as determined by the MC represent the reference point required for the 4QOP method. 4QOP curves given the OP shown in the first row of Table 1 (the MC) are shown for each four quadrant data set in Fig. 5.

Considering only one four quadrant data set, it is easily seen how large of an impact the choice of reference point can have on a system. Fig. 6 shows the very dissimilar 4QBEP and 4QOP curves for one data set against the initial system curve.

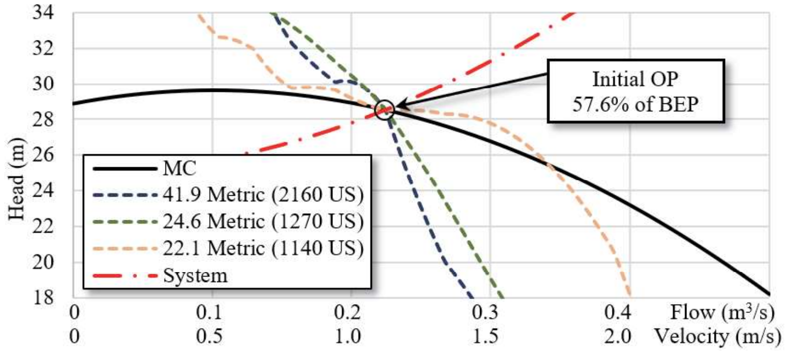


Figure 5. MC and 4QOP for each four quadrant data set, using the conditions described in Table 1 for the MC

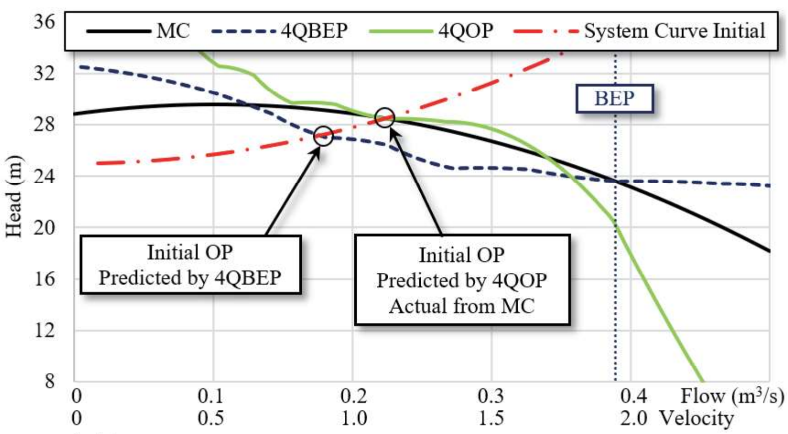


Figure 6. Comparison of MC, 4QOP, and 4QBEP for the Ns = 22.1 Metric (1140 US) data set

4.3 Transient results

The peak maximum and minimum pressures occur at the ESD exit for all cases. The results for Ns = 22.1 Metric (1140 US) are shown in Fig. 7. Since in this example the ESD closes before reverse flow occurs, the pump stays in the first quadrant. The example could be easily changed to allow for a slower closing ESD which allows reverse flow which requires four quadrant methods. Since this pump remains in the first quadrant, the 4QBEP and 4QOP results can be compared to the MC transient torque balance method discussed in Part 1, Section 5. The MC transient is shown in Fig. 7 for comparison and should be considered the most accurate of the three curves. Note that the peak pressures for 4QOP and MC agree quite well and exceed the 4QBEP max and min by roughly 20 m. A max/min pressure profile is shown in Fig. 8 for Ns = 22.1 Metric (1140 US) to give a broader view of the transient response.

The maximum and minimum pressures for each case are summarized in Fig. 9, showing a wide array of conflicting results, with two items of significance:

1. For Ns = 22.1 Metric (1140 US), 4QOP not only predicts higher maximums and lower minimums than the 4QBEP, but also closely agrees with the MC.

2. For the other two data sets, the opposite is true – 4QBEP predicts the highest maximums and lowest minimums, and has closer agreement to the MC.

Based on these results, one cannot make a generalization about whether 4QBEP or 4QOP is more accurate or conservative. Note that if all tank levels were 20 m lower, some of the minimum pressures would be below atmospheric pressure, with others comfortably above vacuum conditions. Hence, depending on the four quadrant data set selected and choice of 4QBEP or 4QOP, an engineer may call for unnecessary vacuum protection, or worse, not request it when it is needed. If the tank levels were lower still, some cases would predict transient cavitation, with similar impact on the selection of surge suppression equipment.

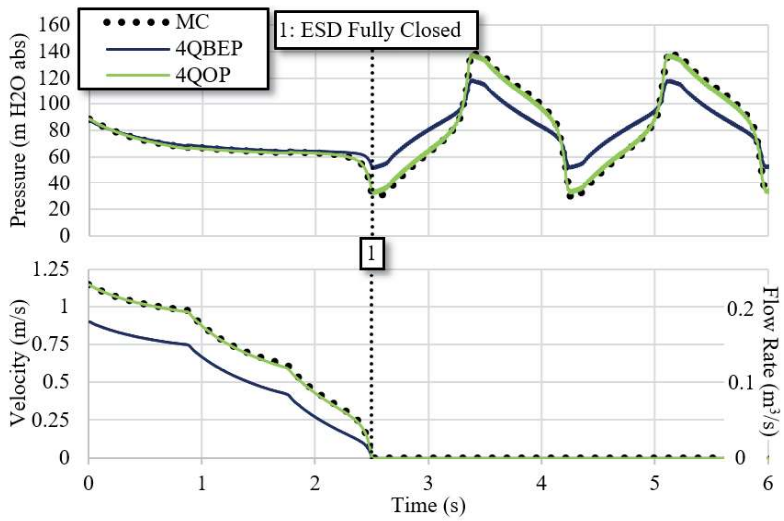


Figure 7. Example 1 results for Ns = 22.1 Metric (1140 US)

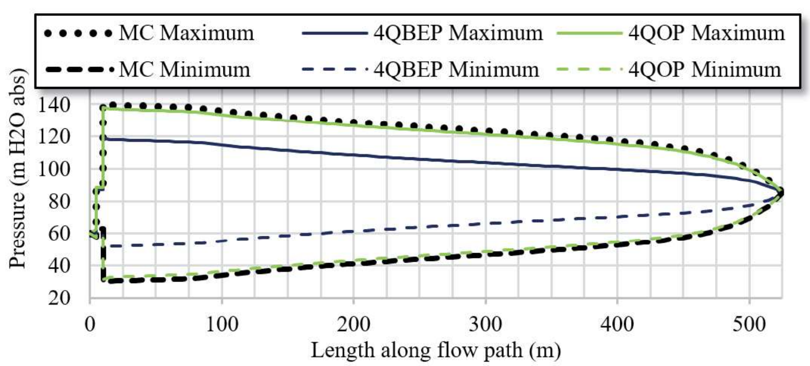
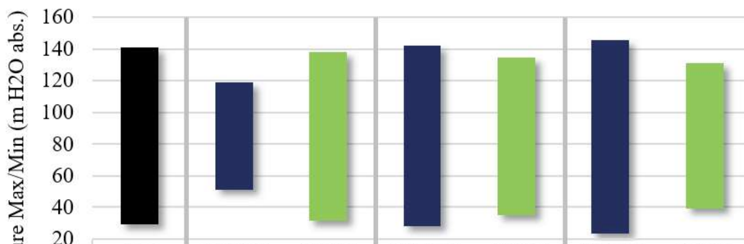


Figure 8. Example 1 pressure profile for Ns = 22.1 Metric (1140 US)



	MC	4QBEP	4QOP	4QBEP	4QOP	4QBEP	4QOP
Ns	32 (1653)	22.1 (1140)		24.6 (1270)		41.9 (2160)	
Max	141	119	138	142	135	146	131
Min	29.1	51.1	31.5	27.9	35	23.4	39.1

Figure 9. Example 1 max and min pressure results for each data set (Ns shown in metric on top and US on bottom, in parentheses)

5 EXAMPLE 2 – PUMP TRIP WITH ESD CLOSURE AFTER FLOW PATH CHANGE

5.1 System configuration and transient data

This example concerns the same system described by Fig. 3. In this case, flow is redirected from the Upper Tank to the Lower Tank. Starting at time zero Valve A closes over 10 seconds while Valve B opens over 10 seconds, following the Fig. 2 profiles. The transient behavior mostly settles out by 20 seconds, when there is an unplanned pump trip. When the pump trips the ESD begins closing over 7 seconds also following the Fig. 2 curve.

5.2 Initial steady-state behavior

The initial steady-state results, system curve, and 4QBEP and 4QOP pump curves are the same as Example 1, discussed in section 4.2. Only the transient events have been modified.

5.3 Steady-state results after valve switch but before pump trip

With the knowledge of the MC and all 4QBEP and 4QOP pump curves, the steady-state conditions for pump flow to the Lower Tank before the pump trips can be determined and are shown in Table 2.

Similar to Fig. 6, it is helpful to draw a set of pump vs system curves comparing the behavior of the different options. Fig. 10 shows the same curves as Fig. 6, but with the final system curve. It is plainly evident that the different options can dramatically affect the final steady-state results.

5.4 Transient results

Changing the flow path from the Upper to the Lower Tank introduces some transient effects. These effects mostly settle out by 20 seconds, at which point the pump trips and the ESD begins closing.

Table 2. Example 2 pump steady-state for each curve after valve switch but before pump trips. The BEP for all cases is 0.39 m³/s

	Ns	Flow (m^3/s)	Vel. (m/s)	Head (m)	% of BEP
MC	32 Metric (1653 US)	0.442	2.25	21.3	113.4
4QBEP	22.1 Metric (1140 US)	0.485	2.47	23.4	124.5
	24.6 Metric (1270 US)	0.437	2.22	21.0	112.1
	41.9 Metric (2160 US)	0.421	2.14	20.3	108.1
4QOP	22.1 Metric (1140 US)	0.395	2.01	19.2	101.3
	24.6 Metric (1270 US)	0.320	1.63	16.4	82.2
	41.9 Metric (2160 US)	0.304	1.55	15.9	78.1

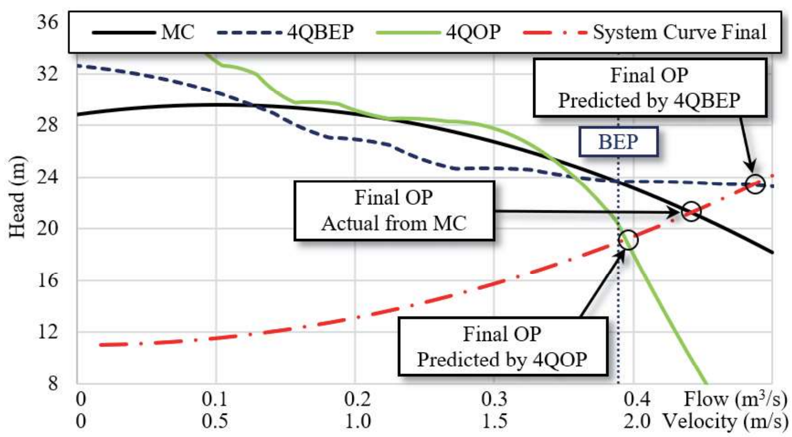


Figure 10. Example 2 Ns = 22.1 Metric (1140 US) curves and system curve before the pump trip. The pump curves are identical to those in Fig. 6

Fig. 11 shows the pressures at the ESD exit for the Ns = 22.1 Metric (1140 US) case. 4QBEP predicts maximum pressures approximately 35 m higher than 4QOP.

The Ns = 41.9 Metric (2160 US) case shows similar transient behavior, as shown in Fig. 12. For this data set, 4QBEP predicts maximum pressures about 25 m higher than 4QOP. Note that the predicted maximum pressures are about 10 m lower than the Ns = 22.1 Metric (1140 US) data set (Fig. 11). This is significant and related only to the choice of four quadrant data set. The minimum pressures follow similar patterns in all the above cases.

It is interesting to see in Fig. 11 that the Ns = 22.1 Metric (1140 US) data set does not predict reverse flow at the ESD or pump for either 4QBEP or 4QOP, while Fig. 12 shows that the Ns = 41.9 Metric (2160 US) data set does predict reverse flow in the 4QOP case.

There is clearly significant disagreement in the velocity predicted by each method in both Figs. 11 & 12. Note the velocities before the pump trips – the transient affects introduced by the valve switch are beginning to die out and the system is reaching a new steady-state.

In fact, these velocities match those predicted by the pump vs system curve shown in Fig. 10 and Table 2. 4QBEP predicts a velocity of approximately 2.4 m/s whereas 4QOP predicts about 2 m/s. The true value, from the MC, is about 2.2 m/s. Similar values are seen in Fig. 11.

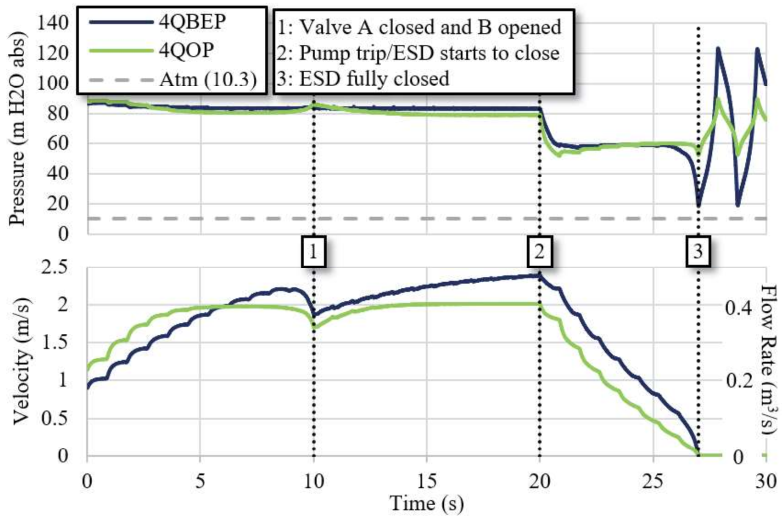


Figure 11. Transient pressure and velocity at exit of ESD for Ns = 22.1 Metric (1140 US)

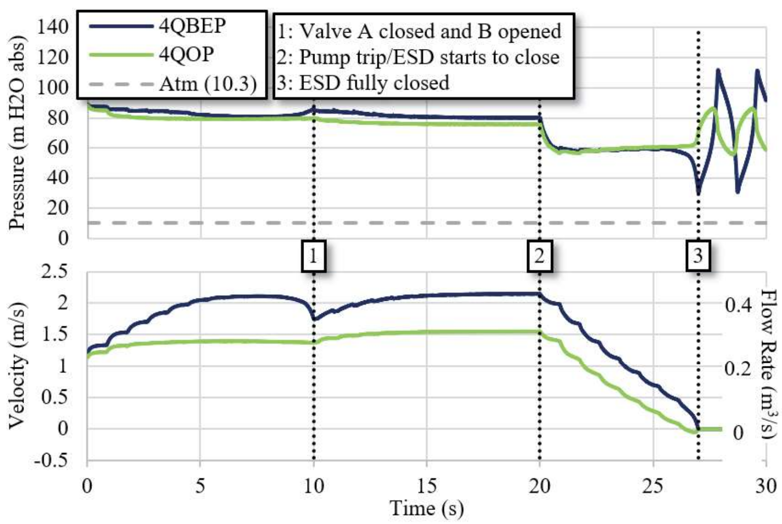


Figure 12. Transient pressure and velocity at exit of ESD for the Ns = 41.9 Metric (2160 US) data set

6 EXAMPLE 3 – PUMP TRIP WITH ESD CLOSURE AFTER FLOW PATH CHANGE WITH PUMP OPERATING NEARER TO BEP

The differences between the 4QOP and 4QBEP methods are strongly linked to how close the initial OP is to BEP. In fact, the methods are identical if the initial OP is exactly BEP.

Using the same system described by Fig. 3, flow is instead switched from the Lower to the Upper Tank. The initial flow to the Lower Tank in this case is 113% of BEP (same as Table 2, MC). Because the OP is much closer to BEP, the 4QOP and 4QBEP curves are much closer to each other, as shown in Fig. 13. 100 m of additional pressure was added to all Tanks in Fig. 3 to avoid cavitation. The flows are not affected but the system pressures increase uniformly by 100 m at all locations for all times.

Following Fig. 3, Valve A starts closed. Valve A opens and Valve B closes over 10 seconds, following Fig. 2. As in Example 2, the pump has an unplanned trip at 20 seconds and the ESD starts closing when the pump trips and closes over 7 seconds.

The transient results (Fig. 14) between 4QBEP and 4QOP look more similar than they do in Example 2. Note, however, that differences still exist. In the Ns = 24.6 Metric (1270 US) case, 4QOP predicts maximum pressures nearly 20 m higher than 4QBEP – a significant difference in many systems. The velocities at 20 seconds (when the pump trips) in Fig. 14 are very different. Further note that agreement between the 4QOP and 4QBEP methods does not necessarily indicate accuracy. The two four quadrant methods could agree very closely with one another, but diverge significantly from the MC.

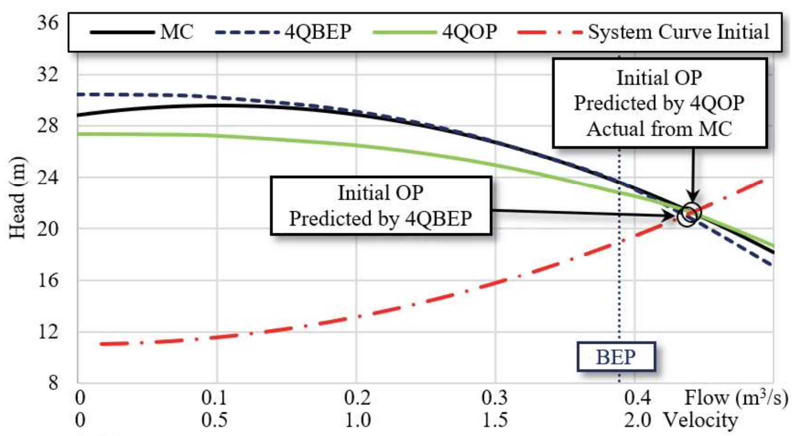


Figure 13. 4QBEP and 4QOP curves when reference OP is near BEP, Ns = 24.6 Metric (1270 US) data set shown here

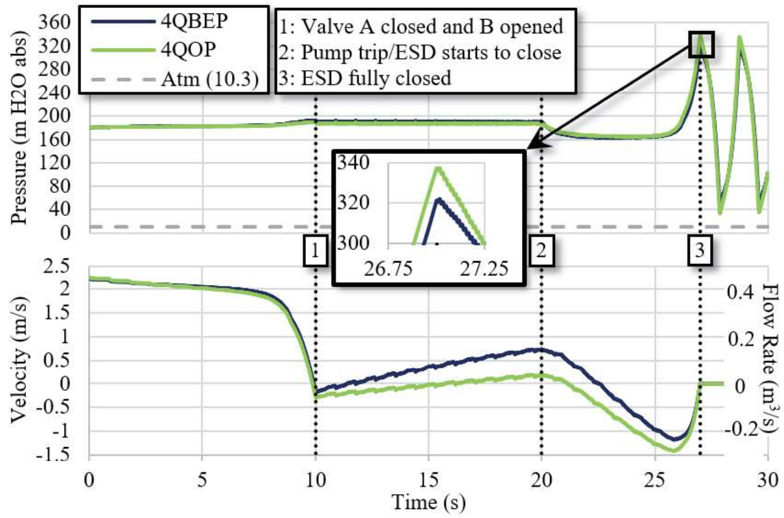


Figure 14. Pressure and velocity at exit of ESD using Ns = 24.6 Metric (1270 US) data set with initial flow to Lower Tank, switching to Upper Tank

7 EXAMPLE 4 – PARALLEL PUMP SYSTEM WITH PUMP TRIP AND CHECK VALVE SLAM

Check valves can slam closed under reverse flow, causing severe pressure surge. An example using two pumps described by Fig. 1 operating in parallel is discussed here. In the system shown in Fig. 15, Valve E starts opening at time zero over 6.25 seconds, following the characteristics in Fig. 2. Valve F remains open throughout the transient. At 10 seconds, Pump C has an unplanned trip. Check Valve C slams closed due to the continued operation of Pump D.

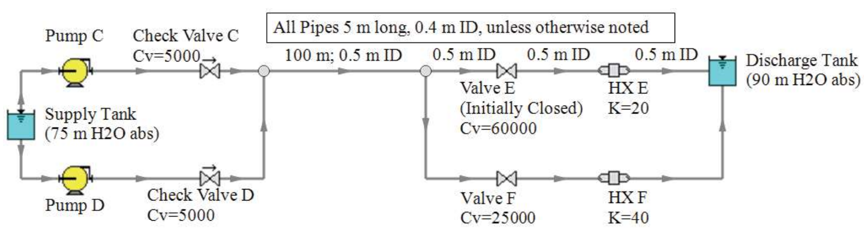


Figure 15. Example 3 schematic

7.1 Initial and final steady-state behaviors without pump trip

Pump vs System curves comparing steady-state behaviors are shown in Figs. 16 & 17.

Because this system ends up operating very close to BEP, 4QBEP agrees very closely with the MC in Fig. 17 for the Final OP. These points are in fact different. Like Example 1, the OP predicted by 4QOP is much different than that predicted by either 4QBEP or the MC. This has significant transient implications.

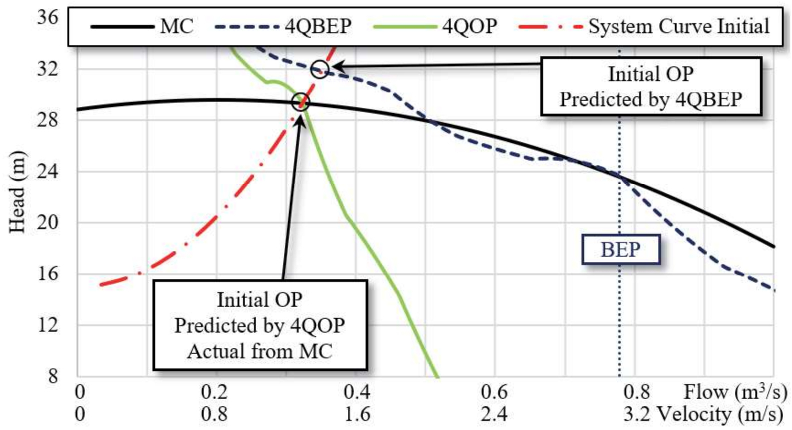


Figure 16. Example 4 pump vs. system curve showing MC, 4QBEP, and 4QOP for the initial conditions, for the Ns = 41.9 Metric (2160 US) four quadrant data set. Velocity is referenced to Pump C

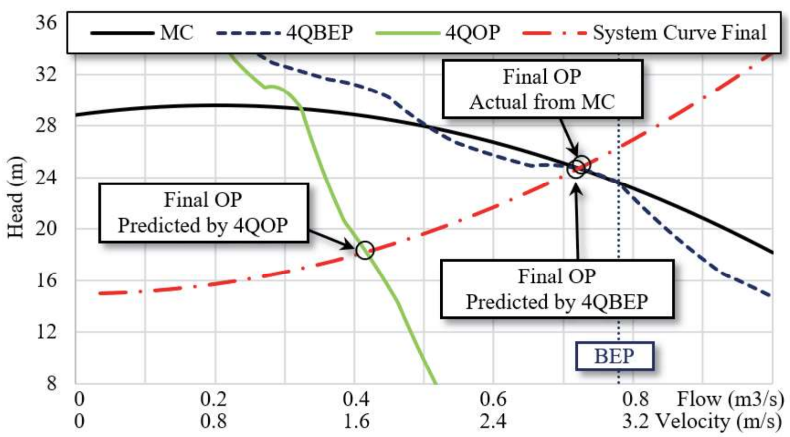


Figure 17. Example 4 pump vs. system curve showing MC, 4QBEP, and 4QOP for the final conditions. Based on Ns = 41.9 Metric (2160 US) four quadrant data set. Velocity is referenced to Pump C

7.2 Unplanned pump trip

After opening Valve E, bringing the additional heat exchanger HX E online, Pump C has an unplanned trip at 10 seconds.

Fig. 18 shows max and min pressures through the Pump C to HX E path for one of the four quadrant data sets. As seen in Fig. 19, the velocities predicted by 4QBEP prior to the Pump C trip (at 10 seconds) are significantly higher than those predicted by 4QOP. Because of this, the predicted check valve deceleration is higher as well. Using swing check valve deceleration charts from Thorley, 2004 (8), a reverse velocity of 0.6 m/s was determined for 4QBEP, and a reverse velocity of 0.3 m/s for 4QOP.

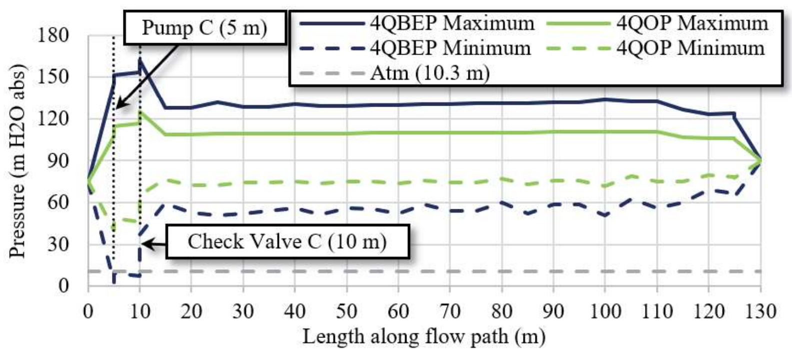


Figure 18. Pressure max/min along path through Check Valve C and Valve E for Ns = 41.9 Metric (2160 US) four quadrant data set

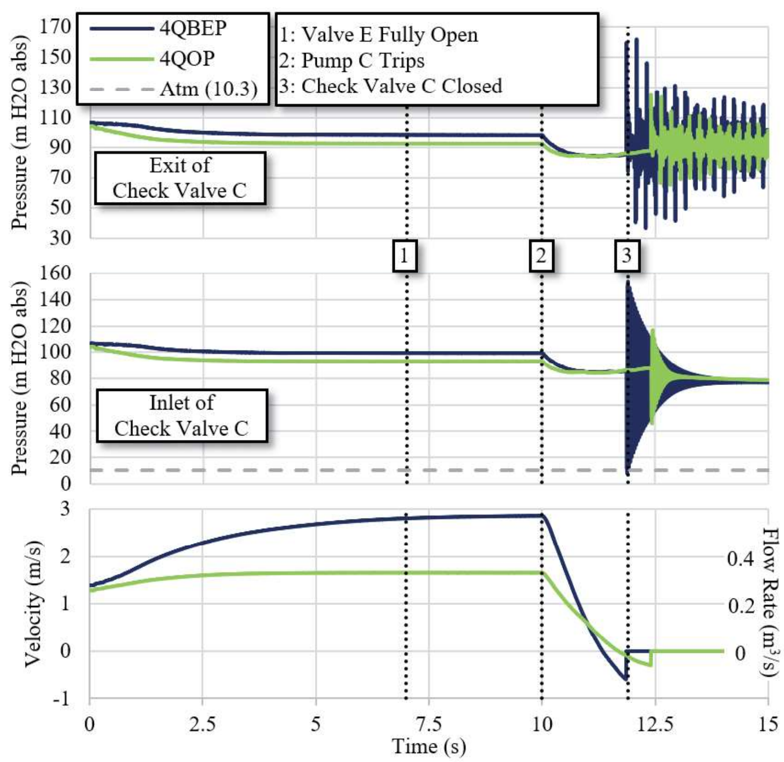


Figure 19. Pressure and velocity at inlet and exit of Check Valve C using Ns = 41.9 Metric (2160 US) data set

With a higher reverse velocity though the check valve during closure, a significantly higher pressure surge results. 4QBEP predicts a maximum pressure of over 160 m, whereas 4QOP predicts maximum pressures under 130 m (see Fig. 18). Additionally, the minimum pressures in the 4QBEP drop below atmospheric pressure, while the 4QOP method remains more than 30 m above atmospheric pressure (Fig. 18).

As before, steady-state analysis of Fig. 17 can predict the velocities seen before the pump trip. The dramatic difference in prediction of 1.6 m/s for 4QOP and 2.8 m/s 4QBEP at 10 seconds is reflected in the transient results of Fig. 19.

Engineers using 4QOP might incorrectly conclude that no protection is needed against vacuum or cavitation conditions. On the other hand, engineers using 4QBEP might install unneeded and potentially expensive surge mitigation. The significant difference in peak pressures highlights the significance of the four quadrant pump curve assumptions in the simulation.

8 RECOMMENDATIONS

The examples in this paper reinforce the authors' belief that substantial sensitivity studies should be completed in waterhammer simulations involving four quadrant data. Both options should be evaluated, and multiple four quadrant data sets near the pump specific speed should be included. Engineers should identify the initial and final steady-states of the system and consider transient simulation results with the steady-state values in mind. Comparisons should be made to MC transient results in the first quadrant (see Part 1, Section 5).

The issues raised in this paper are closely linked to off-BEP operation. However, they still exist and can impact all simulations regardless of BEP. In particular, the choice of four quadrant data set becomes more impactful if the reference point concern is settled. It is the authors' opinion that additional caution should be exercised when analyzing reverse flow of pumps operating far from BEP.

Whenever possible, four quadrant data collected from actual testing of the pump in question should be used. Recognizing that this data is rarely available, it is critical that waterhammer engineers are aware of the impact assumptions embedded in common methods have on transient analyses.

Walters, Lang, and Miller, 2018 (10) provide all raw data files and more complete output such as pump speed decay and torque for all cases in this paper.

9 CONCLUSION

Significant and potentially dangerous differences exist in waterhammer simulation results obtained on four examples related to two conceptual but real world-based systems. These differences resulted from different steady-state and transient assumptions about pump behavior when four quadrant methods are required. Engineers are highly encouraged to expand the scope of their sensitivity studies to account for these differences.

10 ACKNOWLEDGMENTS

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