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Closed systems provide unique challenges for pump selection.

System head curves can be readily developed for pumping systems with a tank on both the suction and discharge side of the pump. However, many pressure zones in water distribution systems do not have a tank on the discharge side of the pump, and the usual methods for creating system head curves do not work for such systems. This article discusses the development of a new method to determine system head curves for closed systems and the implications for pump selection and operation. The analysis indicates that system head curves fluctuate much more widely for systems without discharge-side tanks than they do for those with such tanks.

Developing system head curves for closed systems

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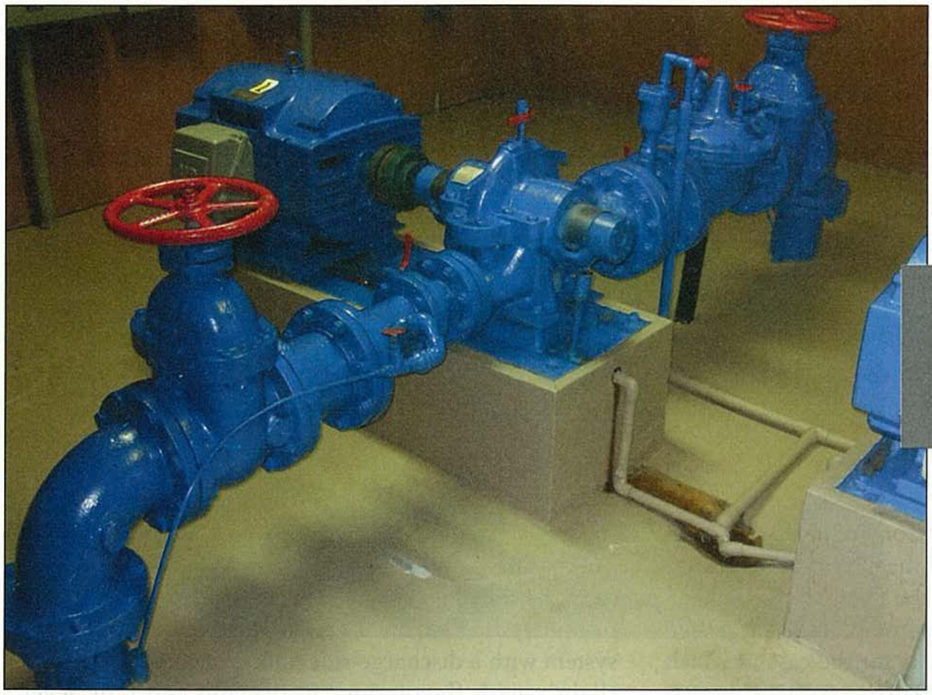
A system head curve is defined as the "relationship between the discharge of a pump and the head it must pump against" (WEF, 2009). The points on the system head curve are a property of the system and are independent of the pump. System head curves are useful for the selection and operation of pumps. The intersection of the system head curve and the pump head characteristics determines the operating point (head and flow) of the pump.

Developing system head curves is a relatively straightforward process for simple systems with a storage node—which could be a tank, reservoir, or hydropneumatic tank—on both the suction and discharge side of the pump. System head curves and their development are described in numerous references (e.g., Jones, 2008; Walski et al, 2003a; Messina, 2001; Bosserman, 1999; Walski & Ormsbee, 1989). This article addresses development of system head curves, first for a simple system in which water is pumped between two tanks, then for a system with no discharge-side tanks (a closed system, i.e., a system with no floating storage on the downstream side of the pump), and finally for complex real-world water distribution systems. Implications for pump selection, system design, and pump operation are also discussed.



Understanding the system head curve can help in pump selection, even for closed systems.

SYSTEM HEAD CURVE DEVELOPMENT AND SYSTEM TYPE

Figure 1 shows the system head curve for a simple system in which water is pumped between two tanks. The two components that make up the head to be overcome by the pump are the head to lift the water from the suction-side tank to the discharge-side tank and the head required to overcome friction and minor losses in the piping. For a simple system with two tanks and no water use between the two tanks, the system head curve can be described by Eq 1:

$$h_p = H_2 - H_1 + kQ^n \qquad (1)$$

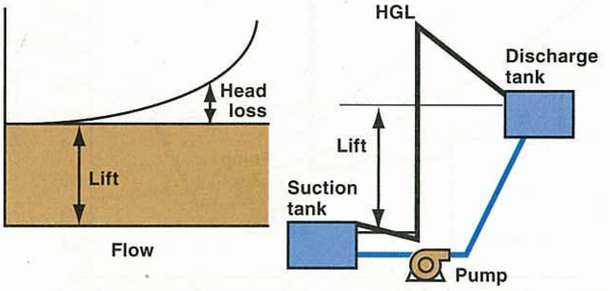
in which h_p is the system head in m, H_1 is the head of the suction side tank in m, H_2 is the head of the discharge side tank in m, k is the coefficient of head loss (including pipe losses and minor losses), Q is the flow in L/s, and n is the exponent in the head loss equation (1.85–2.0).

The problem of developing a system head curve becomes more complicated in real water distribution systems. They are such complex combinations of piping and users that it is generally not possible to determine a simple k value as given in Eq 1 because of the many thousands of paths along which the head loss can be calculated. Instead it becomes necessary to either greatly simplify the hydraulic network or use a hydraulic model of the system to produce the system head curve. Current hydraulic models can automatically generate system head curves provided there is a tank on each side of the pump for which a system head curve is desired. However, these approaches do not work well for complex, closed systems with no discharge-side tank because the basic premise of the models is that demands are fixed. Variations in demand with pressure are difficult to consider in developing a system head curve.

Simple closed system. A closed or dead-end system is not actually closed; if it were, no flow could enter it. Instead of having a tank to receive or discharge water when demand does not equal pump flow, in a closed system all of the flow through the pump must leave the system through orifices (e.g., faucets, sprinklers, showerheads, washing machine fill-line valves) at the user's location. Closed systems are used in locations where floating storage is either undesirable, infeasible, or large hydropneumatic tanks are impractical.

In the simple system shown in Figure 2, all of the pump discharge passes through a single orifice. Given

FIGURE 1 System head curve for a simple two-tank system



HGL—hydraulic grade line

that the head loss through the orifice follows the orifice equation below, the discharge can be related to the flow using Eq 2:

$$Q = K\sqrt{h_o} \tag{2}$$

in which Q is the flow through the orifice and pump in L/s, K is the orifice resistance coefficient, and h_o is the pressure head at the orifice in m.

For a single orifice, elevation of the orifice must be substituted for the head of the discharge tank, and a term for the head loss through the orifice must be inserted into Eq 1 to yield Eq 3:

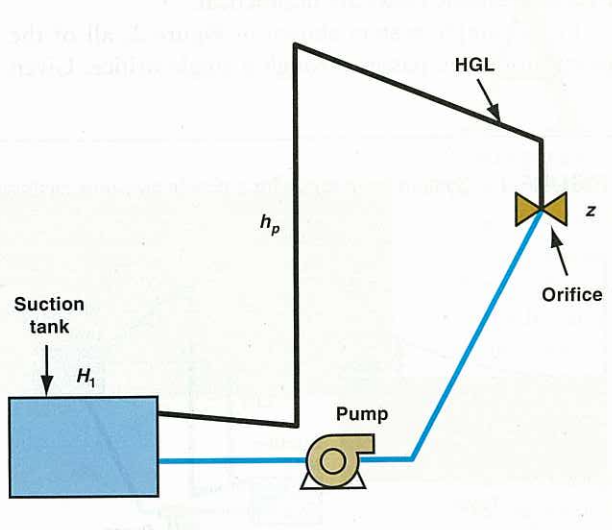
$$h_p = z - H_1 + kQ^n + (Q/K)^2 \tag{3}$$

in which z is the elevation of the orifice in m.

Using some typical values of the parameters in Eqs 1 and 3, it is possible to compare the shape of system head curves for a system with and without a discharge-side tank. Figure 3 shows these results for the case in which $H_1 = 100$ m, $H_2 = 200$ m, $z = 150$ m, $k = 0.005$, $K = 0.01$, and $n = 1.85$.

Figure 3 shows a trend in the comparison of system head curves for systems with and without discharge-side tanks. Systems with tanks will have flatter system head curves because the water level in the tank will be higher than the elevation of the orifices fed from the tank (i.e., the curve starts out higher), but the resistance from orifices results in a steeper curve for systems without tanks. In systems with tanks, a greater portion of the energy is spent lifting the water, whereas in systems without tanks, more of the energy is used to overcome friction and orifice losses. Another way of looking at it is that the orifice adds head loss and that head loss can be represented by additional equivalent pipe length and therefore a steeper system curve.

FIGURE 2 Schematic of simple system with flow to an orifice



H_1—system head of the suction side tank, hp—system head, HGL—hydraulic grade line, z—elevation of the orifice

> In systems with tanks, a greater portion of the energy is spent lifting the water, whereas in systems without tanks, more of the energy is used to overcome friction and orifice losses.

Another characteristic of system head curves that can be studied with these simple systems is the variation in system head curves as water use changes. In a system with a discharge-side tank, the curve varies only slightly with fluctuations in demand and tank level. However, in the system without a discharge-side tank, the head varies greatly as consumers use more water (i.e., open more orifices) or open them wider during peak demand times than in off-peak demand times. This large variation over time in a closed (no tank) system is shown in Figure 4. The three curves in the figure correspond to the typical range of water use (minimum, average, maximum) over the course of the day with $K = 0.005$, 0.01, and 0.02.

Realistic closed systems. The simple systems described in the preceding section provide insight into system head curves. However, real water distribution systems are so much more complex that hydraulic models must be used to solve the network equations. These models usually solve for the system head curves by breaking the overall system into separate models for the suction and discharge side of the pump and comparing the heads across the pump to determine the values for the system head at each pump flow rate. This logic breaks down, however, when there is no discharge-side tank.

Instead, it is necessary to describe the relationship between demand and pressure using the concept of pressure-dependent demand (Wu et al, 2009). With pressure-dependent demand modeling, it is essential to specify a function relating the actual demand by a user to the actual pressure at the point of use. Typically, the orifice equation in Eq 2 is used, but the formulation is sufficiently general to allow any monotonically increasing function of pressure head and demand. Before development of models that accounted for pressure-dependent demand, the effect of this demand on system head curves could be calculated by replacing the demand at each node with an emitter coefficient at the elevation of the demand. Although this approach would work for one

Having an accurate system head curve enables operators to determine better operating points for pumps.

steady-flow condition, the coefficients need to be adjusted for each flow rate. Calculating water use on the basis of pressure is essentially what is done with pressure-dependent demand, but the calculations are performed without intervention by the modeler, even for extended period simulations.

This approach was applied to a model of an actual small water distribution system with 105 pipes and 85 junction nodes and a typical demand of 60 L/s (950 gpm). Figure 5 shows the resulting head curve for this system, developed using a water distribution modeling program.[1]

The curves in Figure 5 show a shape similar to the system head curves in Figure 4. This indicates that as water users open and close faucets and other orifices over the course of a day, the system head curve can vary significantly.

Another analysis was conducted to examine the effect of modeling half of the demand as pressure-dependent demand and half as fixed demand. (The mix of fixed demand and pressure-dependent demand is system-specific and depends on the nature of the water users.) Results of those model runs are shown in Figure 6. Over much of the range of heads, the curves in Figure 5 and 6

FIGURE 3 System head curves for systems with and without a discharge-side tank

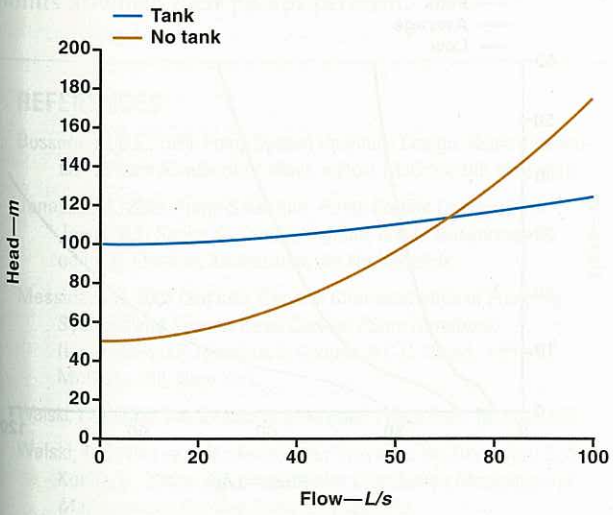
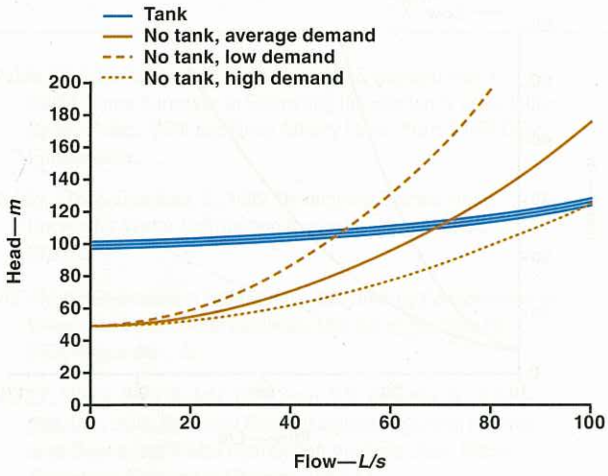


FIGURE 4 Comparison of system head curves at various levels of demand for systems with and without a discharge-side tank



are similar. As shown in Figure 6, at very low heads (i.e., the lowest customer is only a few metres above the water level in the suction-side tank), the fixed-flow component of the demand is attempting to suck water through the pump. A hydraulic engineer would not design a system to work in this range, and software with fixed-demand modeling provides a somewhat misleading result. For a practical range of flow, including some fixed demands, the model still provides valid results. The primary finding is that the shape of the system head curve in the range of the operating point is not heavily dependent on the mix of pressure-dependent demand and fixed demand as long as there is some reasonable allowance for pressure-dependent demand.

As water users open and close faucets and other orifices over the course of a day, the system head curve can vary significantly.

Implications for pump selection and operation. The curves shown in the figures indicate that the system head for closed systems varies significantly over time because of varying rates of water use. Overlaying a typical pump head characteristic curve for a constant-speed pump on top of such system head curves shows that the pump operating point fluctuates widely over time. The operating point for a closed system will vary more widely than a system with a discharge-side tank. Because pump efficiency is a function of flow, at times a pump can run fairly inefficiently. Several approaches to reduce such inefficiency are available.

The best way to avoid the inefficiencies associated with closed systems is to install a tank on the discharge side of the pump. This enables the pump to run efficiently when it is on and then turn off (and realize the associated energy savings) when the tank is full. Tanks also provide benefits in terms of reliability, fire protection, and transient control. However, for reasons mentioned previously, tanks are not always feasible.

If a tank cannot be installed, the usual solution is to install a variable-speed pump (i.e., a pump with a variable-speed drive). Although a variable-speed pump runs more efficiently than a constant-speed pump over a wider range of flows, even with variable-speed pumps there are inefficiencies associated with any deviation in pump discharge. In fact, the variable-speed drive itself introduces inefficiencies. Some engineers wrongly assume that if they select a pump to operate efficiently at full speed, then the variable-speed drive will ensure that the pump is efficient at other speeds. With the improved method described here for determining system head curves at other demand conditions, the engineer can more easily evaluate the energy cost of the pumps at many operating points. Discussions of the advantages and disadvantages of variable-speed pumping are available elsewhere (WEF, 2009; Jones, 2008; Walski, 2005; Walski et al, 2003b).

FIGURE 5 System head curves showing pressure-dependent demand for a real system

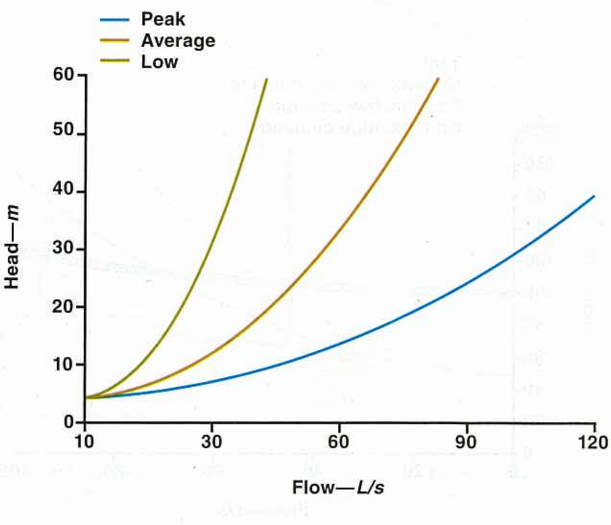
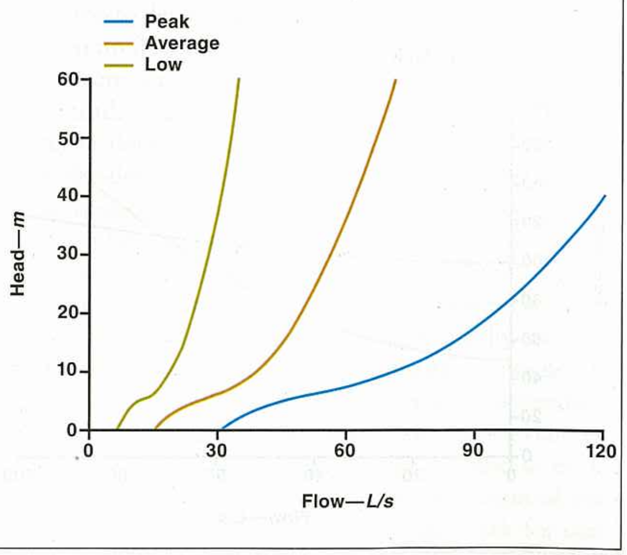


FIGURE 6 System head curves with 50% fixed and 50% pressure-dependent demand



In some situations, it may be more advantageous to install pumps of several different sizes in a pump station so that the pump that is running matches the demand; this enables the operator to run the pumps that are most efficient at a given demand. For example, a small jockey pump could be run during off-peak hours and a larger pump during peak demand times.

In any case, a full life-cycle cost analysis should be conducted before any pump selection. The analysis should consider the range of flows that will be encountered by the pump station and the fraction of time those flows are required, not simply at the best efficiency point of the pump. Engineers who do not have information about the actual operating point may assume the pump is operating at the best efficiency point, which can be misleading. These calculations can best be performed with a hydraulic model with energy-costing capability.

With the improved method described here for determining system head curves at other demand conditions, the engineer can more easily evaluate the energy cost of the pumps at many operating points.

In terms of pump operation, it is essential that water treament plant operators set the pump controls so that the best pump and pump speed are selected in order to match the demands at that point in time. Excessive pressures not only waste energy but also exacerbate leakage problems and increase maintenance costs. Use of the system head curves described in this article will enable operators to better understand the range of operating points at which their pumps perform.

SUMMARY

Hydraulic models now exist that can determine system head curves even for closed systems. These models work by accurately capturing the pressure-versus-demand relationships at water consumers' taps.

The calculations indicate that system head curves are steeper and vary much more widely for systems with no discharge-side tank than for systems with such a tank. This factor should be considered in both pump selection and setup of operational controls.

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FOOTNOTES

[1] WaterGEMS, Bentley Systems Inc., Exton, Pa.

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