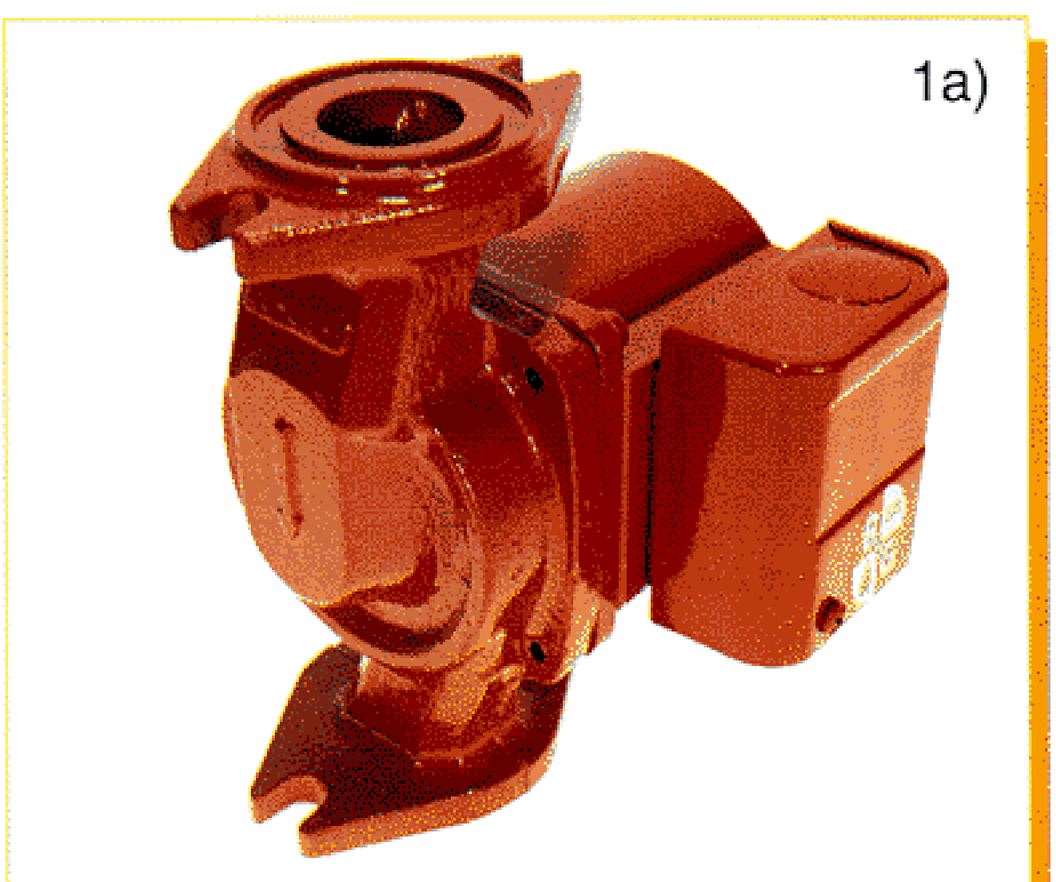
Circulators and closed systems

Circulators are essential elements of heating and air-conditioning (HVAC) systems, where they pump fluid around a closed loop. Roy Ahlgren of Bell & Gossett, a unit of ITT Industries in the USA, unravels the theory behind the operation of pumps in closed systems and considers the different types of circulators in common use in the HVAC industry.

A circulator is simply a pump applied to a closed system. It moves the same liquid around a piping loop over and over. That is a little unusual from the point of view of pumping systems in general, so circulators represent a special case in terms of most pump applications, but it is a very important special case for the heating and air-conditioning (HVAC) industry.

Closed systems

In HVAC 'hydronic' systems, the pumped liquid carries heat from one point to another as it circulates, picking up heat from a high temperature source like a boiler, and dropping it off at some lower temperature destination like a heating system coil. In a chilled water system, the liquid picks up heat at an air-conditioning coil, then drops it off at a lower temperature destination like a chiller evaporator.



Closed systems can be defined in several ways:

- The piping system is completely full of liquid under pressure, in contact with a compressible gas at only one point. That point is usually a 'compression tank'. (Note: some large systems use thermal storage in open tanks as part of the circulating system.)
- The same heat transfer liquid circulates with very little loss and, consequently, very little need for make-up. Most systems use water, which may contain some additives that retard corrosion, etc., but do not alter the properties of the water significantly in terms of pump operation. Some systems use special heat transfer oils, or water with significant concentrations of glycol antifreeze. Major alteration of liquid properties such as specific heat and viscosity must be considered in selection of the circulator. For the rest of this article, assume that water is the circulating liquid.
- Elevation differences may or may not exist, e.g. the piping loop may be vertical or horizontal, but these differences have no effect in determining pump head.
- Pressure differences may exist between various places in the system, but these differences have no effect in determining pump head.

Pump head

The pump's role in any system is to apply work to the system liquid. Generally, the applied work is required to overcome pressure differences or elevation differences in the system, and these are the major factors that determine pump head requirements. And generally, the friction loss encountered by the liquid as it rubs against the piping components

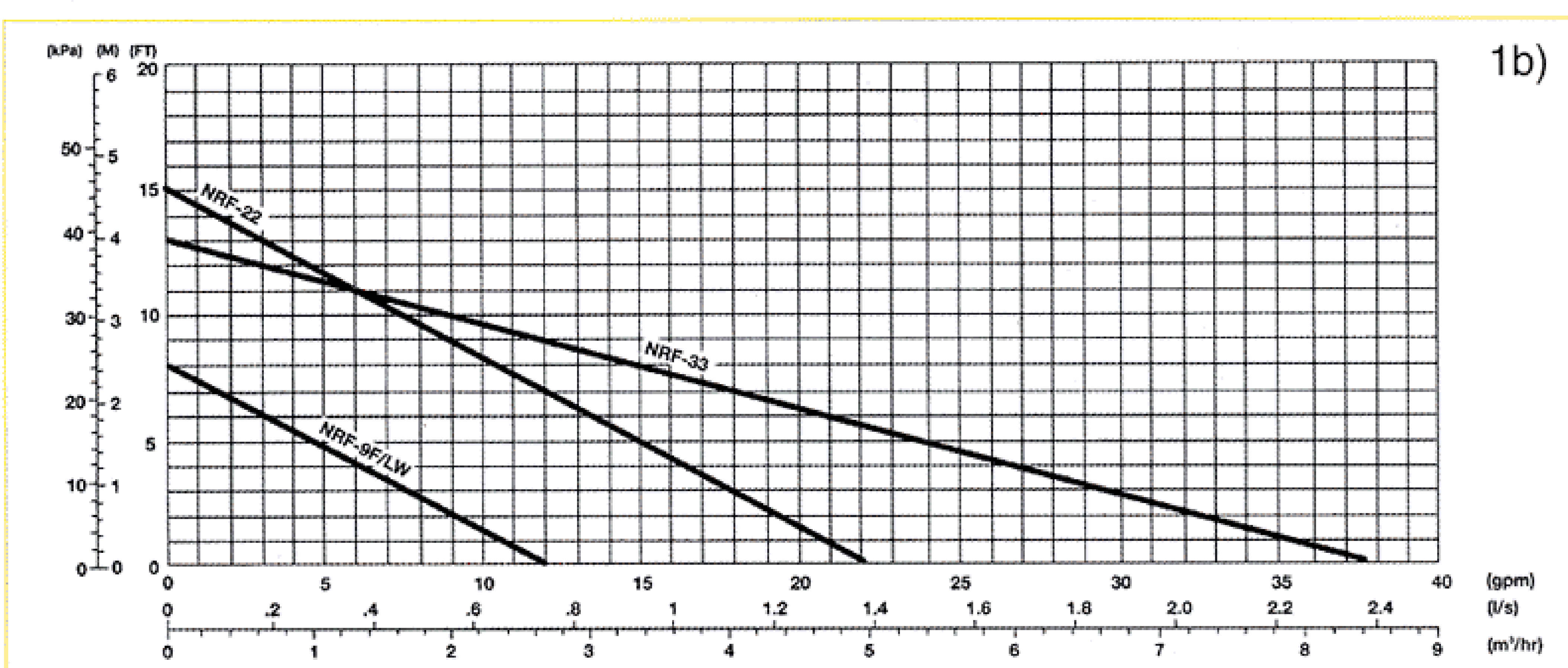


Figure 1.
(a) Small, close coupled, wet rotor pumps such as the maintenance-free 'NRF' from Bell & Gossett (B&G) are typical of heating systems in many US family homes.
(b) Typical NRF pump curves.

represents only a minor factor in determining the pump head required.

Pump head is measured in units of feet of head, or 'foot-pounds of energy per pound of liquid'. Bernoulli's Equation describes this in mathematical form:

$$E_{pump} = \left[\frac{P_b}{W} - \frac{P_a}{W}\right] + \left[Z_b - Z_a\right] + \left[\frac{V_b^2}{2g} - \frac{V_a^2}{2g}\right] + h_{friction}$$

where E_{pump}, is the pump head, measured in feet; P, the pressure on the surface of the liquid at the suction and the discharge, measured in pounds per square foot; W, the density of the liquid in pounds per cubic foot; Z, the elevation of the fluid at discharge and suction, in feet above some reference level; V, the velocity of the liquid at discharge and suction, in feet per second; g, the gravitational acceleration, about 32.2 feet per second per second; $h_{friction}$, the friction head loss in feet; and a and b are arbitrarily selected points on the suction and discharge sides of the system.

In the special case of determining circulator head requirements, points 'a' and 'b' could be the same point, reflecting the fact that the circulating liquid never leaves the system, but simply circulates. If points 'a' and 'b' are the same point, then the first three terms of the Bernoulli Equation must be zero, since there cannot be two different pressures, elevations, or velocities at the same point and time. This amounts to yet another very important definition of a closed system:

In a closed system, pump head is determined only by system friction head loss. Although several experimenters have published pipe friction head loss relationships, most HVAC engineers use the Darcy-Weisbach expression:

$$h_{friction} = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

where $h_{friction}$ and g are defined as above; f is the friction factor, which has no dimensions; L, pipe length in feet; D, pipe diameter in feet; and V, is the average liquid velocity in feet per second.

Of course systems consist of more than just pipes. Friction losses in fittings and manufactured components like coils and boilers also have to be included, but from the circulator's point of view, the total friction loss of all these components at design flow is the only important consideration in determining pump head.

Design flow rate

Since a hydronic system is designed to maintain comfortable indoor conditions in spite of weather changes outdoors, it follows that the design flow rate depends on the 'worst case' temperature difference between the outside and inside. Hydronic system flow rates are calculated by estimating the amount of heat to be transferred in order to maintain acceptable environmental conditions inside a building in spite of outside conditions. Another important factor in determining flow rate is the design 'delta tee', or the temperature change that must occur in the water in order to transfer the design heat load. Designers avoid very high water temperatures since they could be unsafe or difficult to control. [High temperature water systems have been successfully installed in some larger applications, but 250 °F (120 °C) is the more common upper limit.] In chilled water systems, very low temperatures must be avoided to prevent freeze-up of the chiller evaporator. A very common design delta tee for heating systems is 20 °F. Plain water has a specific heat of 1 BTU/LB °F, so at a 20 °F delta tee, the flow required would be:

$$\text{Flow(gpm)} = \frac{\text{Heat Load (BTU/hr)}}{10{,}000}$$

Additives like glycol can decrease the specific heat enough to require a large increase in the flow rate, all other things being equal. The greater viscosity of the glycol mixture will increase system friction loss and lower pump efficiency too.

Circulator types

Any kind of pump could be used as a circulator but, in practice, the HVAC industry has narrowed the pump types actually in use quite a bit. Some of the factors that have driven this 'narrowing' include the following general observations. Minimum initial cost and low operating costs are important factors in the HVAC world. Although new

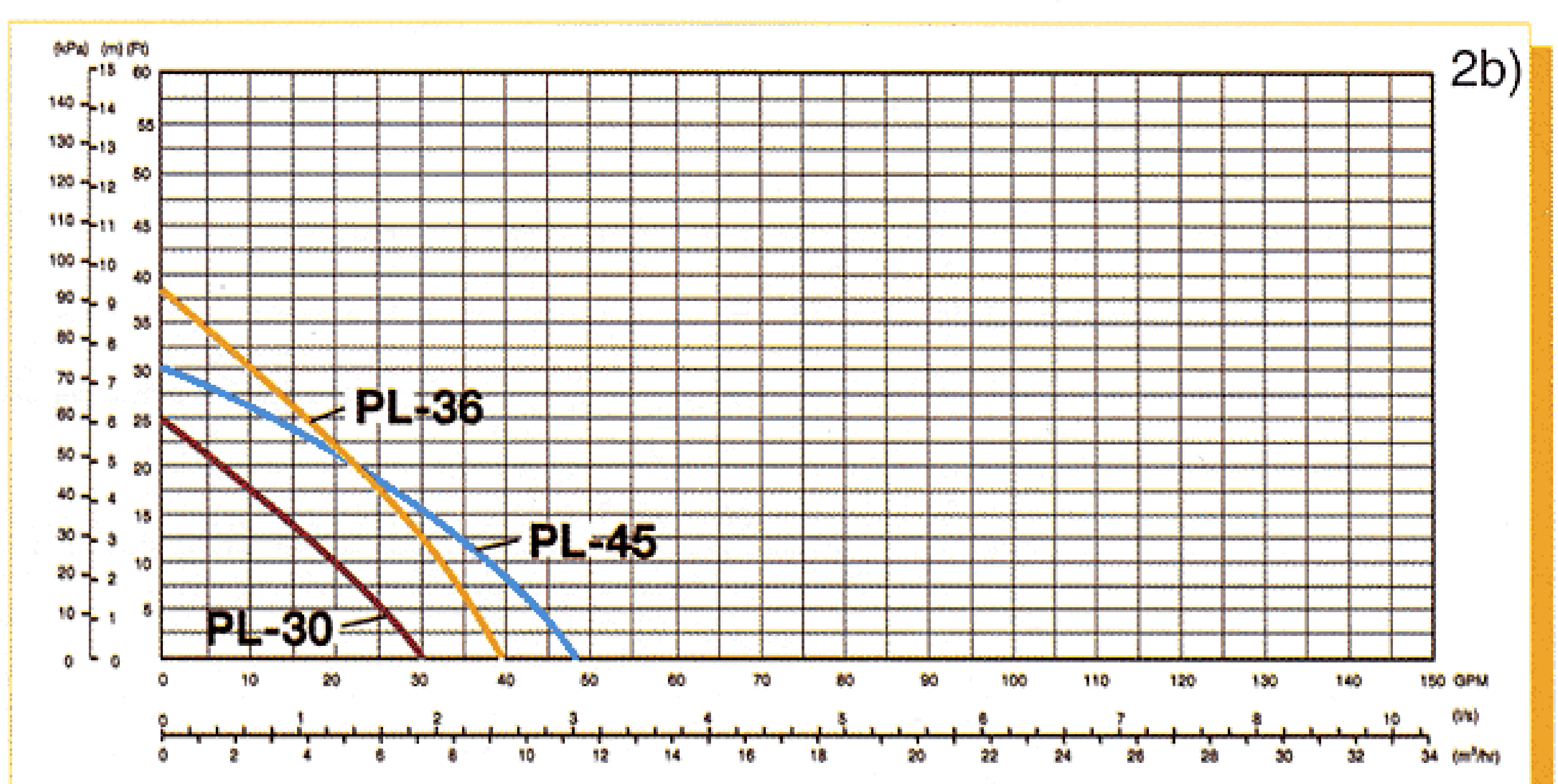


Figure 2.
(a) B&G's PL series of maintenance-free circulators provide an alternative to large wet rotor pumps.
(b) Pump curves for PL series models 30, 36 and 45.

buildings may have very large construction budgets, the amount allocated to mechanical systems is often relatively small.

Pump reliability and ease of maintenance are also important since many HVAC systems have only limited maintenance and technical support. Unlike a process plant that may have a large staff of technicians and millwrights, the typical HVAC system will be operated by relatively less experienced technicians, such as the building janitor. Quiet operation is required since many circulators are installed close to occupied spaces. High efficiency, centrifugal impellers with single volutes seem to be the most commonly used circulators. Both close coupled and flexibly coupled designs are common.

Small circulators

'Wet rotor' circulators

Many single-family homes, especially in the northeastern part of the USA, are heated by small hydronic heating systems. Many of these systems use a small, close coupled, wet rotor pump like the one in Figure 1. The pump curve is typical for this type of pump (Figure 1b). The 40–125 W motor is integrated into the pump. The building heat loss is small; therefore the hydronic system's flow rate and friction loss are also very small. The wet rotor design eliminates the need for a mechanical seal resulting in a very low cost pump. The disadvantage to these pumps is that the hydronic system water often contains high concentrations of small, very abrasive rust particles that can cause bearing failure. These are sometimes considered throw-away pumps since they can be replaced much more easily than they can be repaired.

Circulators that are similar to the wet rotor designs have been developed using permanently lubricated bearings and standard mechanical seals to avoid the bearing problems of wet rotor pumps. Essentially the same design, they come in a larger range of sizes (Figure 2).

Three piece 'booster'

When most people think of 'circulators', they picture the traditional 'three piece circulator' or 'booster' pump as shown in Figure 3. This flexibly coupled, mechanical seal pump used an in-line volute and single suction radial impeller to augment, or 'boost' the circulation in old systems, hence the 'booster' nickname. These older systems were originally designed with no pump at all, using the density differences between hot and cool water to provide circulation. Introduction of the first 'boosters' in the mid-1930s marked the beginning of modern hydronic systems. The three pieces include the pump volute, bearing assembly and motor with its mounting bracket. A special kind of coupler that uses springs in tension, the oil lubricated, sleeve bearings in both the motor and the pump are all designed to provide quiet operation.

All of these small circulators are made in a variety of sizes; the designer simply selects the model and size required to provide design head and flow. Each of these smaller circulators comes with a given impeller and motor, so there are no other choices to be made.

Larger circulators are required for larger systems with greater heat loads and higher total friction loss. These circulators are much like any centrifugal pump used in an industrial system. In-line, end-suction and double suction circulators are all available. One thing they all have in common is the use of a mechanical seal. Packed type pumps have been found to be ill suited as circulators because of the gland leak-off required to cool and lubricate the packing. Remember that the typical hydronic system is designed to operate above atmospheric pressure at all times. If packed type pumps were used, the gland leak-off would have to be made up in order to maintain system pressure. This constant addition of new water would also introduce dissolved air and solids that could corrode or build up scale on the system heat transfer surfaces.

Compression tank

It goes without saying that all circulators must be properly installed in the system, following the manufacturer's recommendations. In this respect, circulators are no different from any other pump, but there is a special requirement that is often misunderstood in the special case of the closed system circulator. The pump must be properly installed with respect to the system compression tank.

Figure 3. (a) Typical three-piece oil lubricated circulators, the Series 100 from B&G.
(b) Pump curves for the Series 100 circulators.

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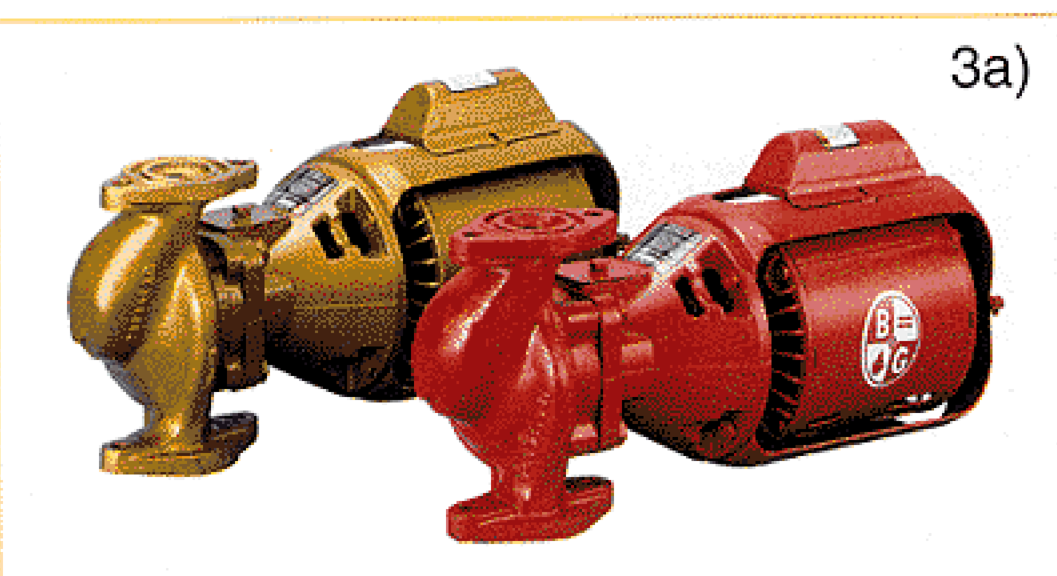

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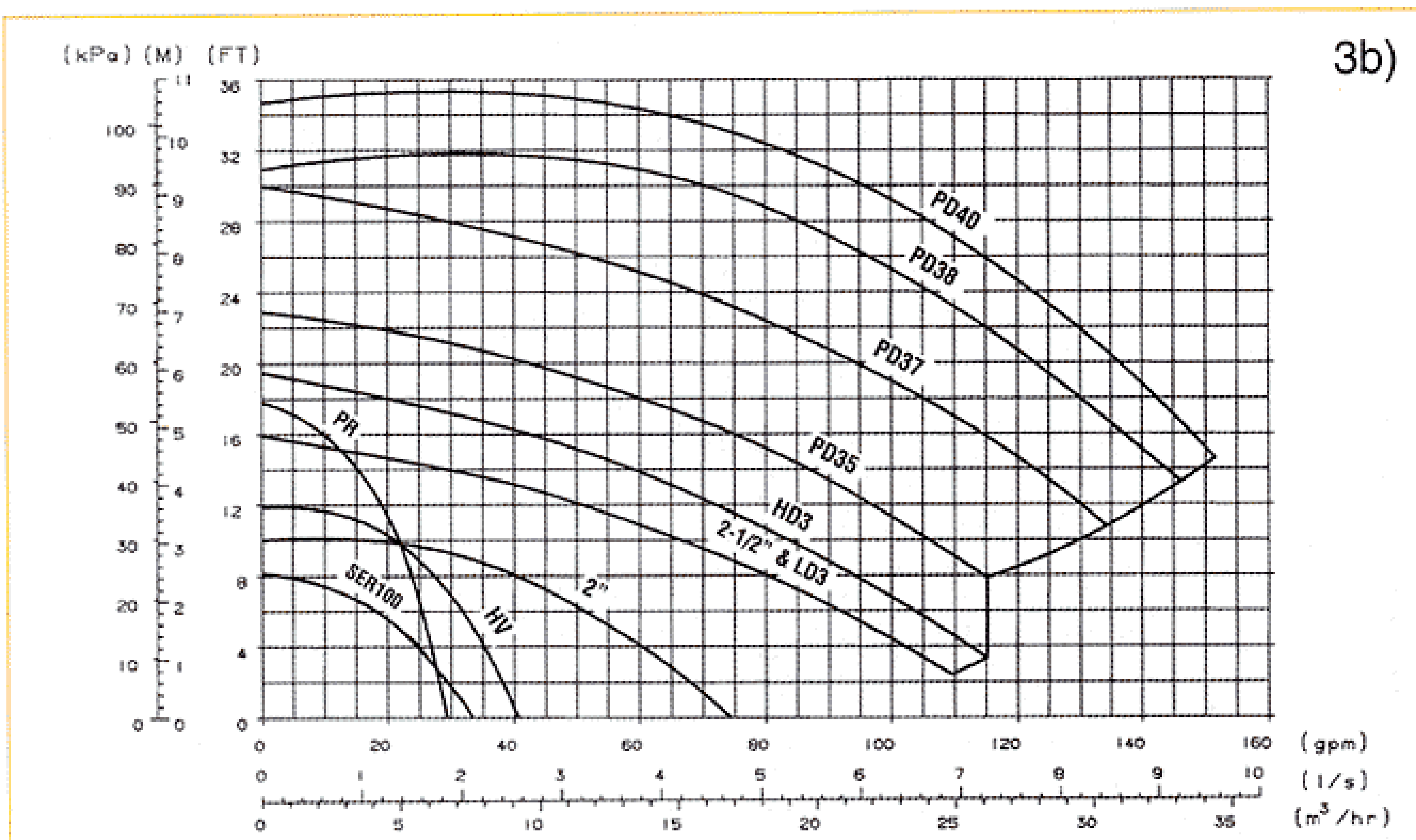

Compression tanks, or expansion tanks as they are sometimes called, are required in order to establish and maintain the system pressure within an acceptable band. The lower limit of this band is established by factors such as the height of the system, and the NPSHR of the pump. The system pressure relief valve setting determines the upper limit of the band. A properly sized tank will contain a gas cushion large enough to allow the system temperature to rise and fall as required, accepting the increase in water volume to raise pressure as the system heats up, then allowing the gas cushion to expand as the average water temperature decreases. At first glance, the location of the pump with respect to the tank may seem to be irrelevant, but it is not because the pressure exerted by the tank on the system cannot be affected by operation of the pump. Bell & Gossett's Gil Carlson, who was responsible for much of the closed system design guidance used today, first stated this concept of the 'point of no pressure change'.

Any of three things can change the pressure at the point where the compression tank connects to the system:

- A change in the amount of water in the system.
- A change in the amount of gas trapped in the compression tank.
- Appreciable change in the volume of the water due to a change in its temperature.

Each of these will have the effect of changing the proportion of gas and water in the compression tank. The circulator can't accomplish any of these changes since it cannot change the amount of air or water in the system, and the heat that it adds as water horsepower degrades by friction is very small compared to the design heat load. Therefore, the tank connection to the system is the 'point of no pressure change', so far as operation of the pump is concerned. In systems where the pump head, measured in pressure terms, is about the same as the cold system pressure, the tank must always be installed at the suction side of the pump, as Figure 4 illustrates.

In Figure 4, assume that the system is a horizontal loop, in order in avoid the static pressure effect and make the analysis that much simpler. With the pump off, the pressure everywhere in the loop has the same value: the result of filling the system, establishing the required cold fill pressure, and allowing for any thermal expansion. When the pump comes on, its differential head causes flow and friction loss, so the pressures measured in that horizontal loop are no longer equal. Since the pump can not change the pressure at the tank connection, there will be a small drop in pressure between the tank and the pump suction, but most of the system will see a rise in pressure due to operation of the pump. If the pump is installed so that it pumps towards the tank, most of the system will see a decrease in pressure when the pump comes on. In a heating system, this decrease could possibly cause boiling and severe noise; in any system, a large decrease could actually create a vacuum, and suck in air through an automatic vent valve, causing corrosion and loss of thermal conductivity in the system heat transfer devices. Installing the pump so that it 'pumps away' from the compression tank will ensure that the pump always adds to the pressure in the system.

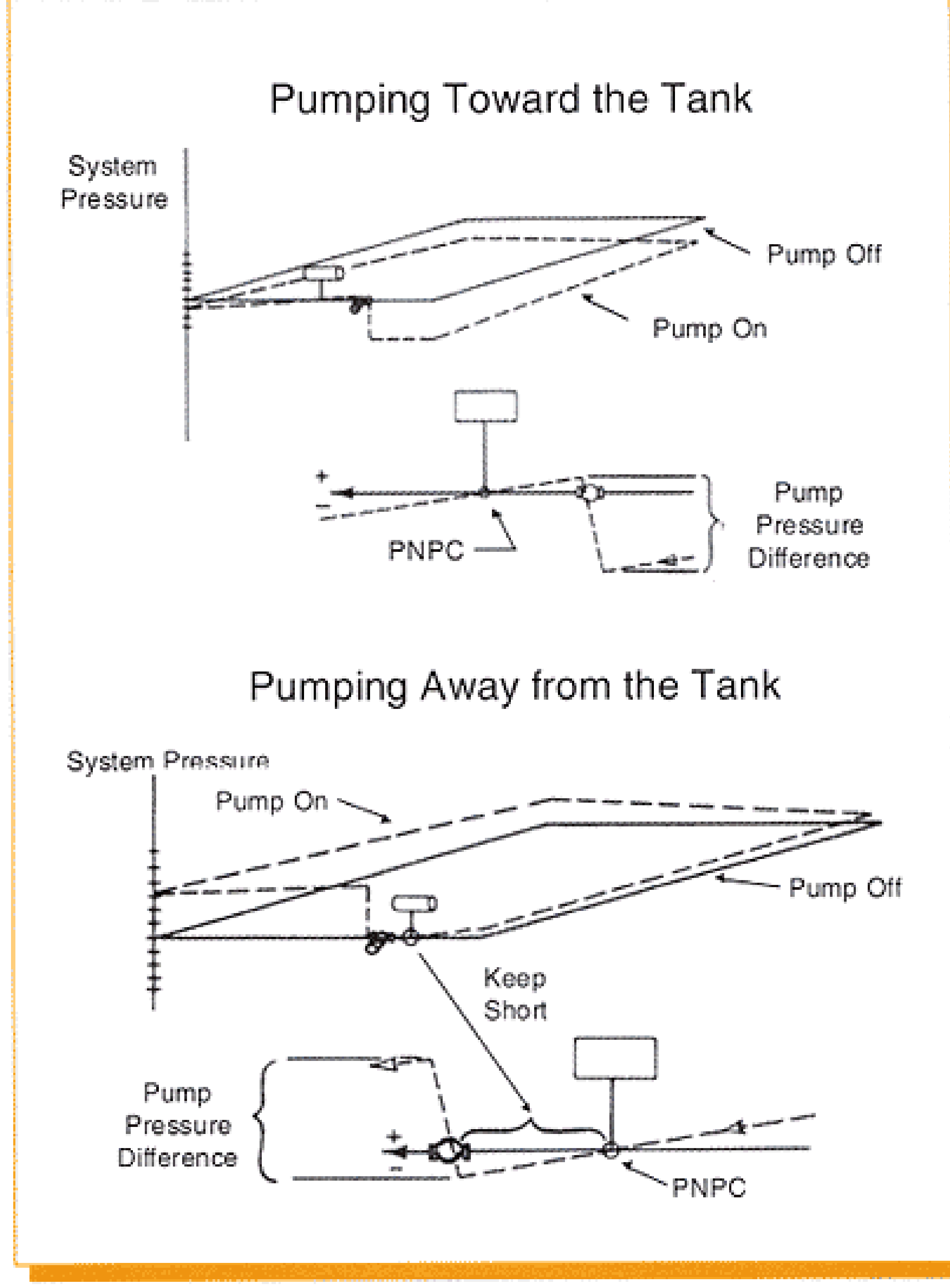

Figure 4. The pump should always be installed such that it pumps away from the compression tank in order to avoid a detrimental decrease in pressure in the system.

In summary, centrifugal pumps used as circulators have many things in common with the pumps found in more general installations, but the designer must be aware of the important differences that exist in this special kind of pump application.

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