FIELD MEASUREMENTS 5

5.0 REAL LIVE MEASUREMENTS

Often field measurements are required to establish or confirm our analysis of a particular situation or problem. This chapter proposes some methods for calculating various heads in the system by using pressure measurements.

5.1 TOTAL HEAD

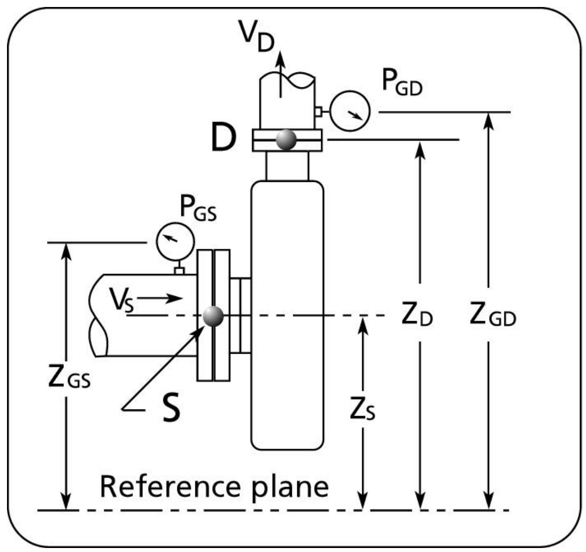

Figure 5-1 pump discharge and suction gauge locations.

The ideal place to locate pressure gauges is as close as possible to the discharge and suction flange of the pump. Total Head is proportional to the difference between these two measurements.

Typically, the measurements will be taken with readily available pressure gauges calibrated in pounds per square inch gauge or psig.

The pressure gage GS must be close enough to point S (see Figure 5-1) so that there is no appreciable friction loss or velocity change along the liquid path between the two points. The pressure gauge GD should also be located close to the discharge flange of the pump.

By definition (see reference 1), the Total Head of the pump is the specific energy, or head, at the discharge, minus the head at the suction:

$$\Delta H_P = \bar{E}_D - \bar{E}_S \qquad [5\text{-}1]$$

the head at the discharge $\bar{E}_D$ is:

$$\bar{E}_D = H_D + \frac{v_D^{\,2}}{2g} + z_D - z_S \qquad [5\text{-}2]$$

and the head at the suction $\bar{E}_S$ is (see chapter 3):

$$\bar{E}_S = H_S + \frac{v_S^{\,2}}{2g} \qquad [5\text{-}3]$$

After equations [5-3] and [5-2] are substituted in equation [5-1] we obtain:

$$\Delta H_P = \frac{1}{2g}(v_D{}^2 - v_S{}^2) + z_D - z_S + H_D - H_S \qquad [5\text{-}4]$$

Since the pressure gauge GS is higher than the pump suction centerline where we require the pressure measurement, we have to correct the pressure reading for height by adding this difference in height to the pressure reading. The same is true for the pressure measurement of gauge GD.

The relationship between the pressure reading and the pressure head is:

$$H_{GD}(ft\ fluid) = 2.31\frac{p_{GD}(psig)}{SG}\ and\ \ H_{GS}(ft\ fluid) = 2.31\frac{p_{GS}(psig)}{SG} \qquad [5\text{-}5]$$

After a correction for height the pressure head H_D at point D is:

$$H_D(ft\ fluid) = 2.31\frac{p_{GD}(psig)}{SG} + (z_{GD} - z_D) \qquad [5\text{-}6]$$

The pressure head H_S at points S is:

$$H_S(ft\ fluid) = 2.31\frac{p_{GS}(psig)}{SG} + (z_{GS} - z_S) \qquad [5\text{-}7]$$

By substituting equations [5-7] and [5-6] into [5-4] we obtain equation [5-8] which is the equation for Total head as measured by two pressure gauges:

$$\Delta H_P\,(ft\ fluid) = \frac{1}{2g}(v_D{}^2 - v_S{}^2) + z_D - z_S - (z_{GS} - z_S) + z_{GD} - z_D + 2.31\ \frac{p_{GD}(psig) - p_{GS}(psig)}{SG}$$

And after simplification, we obtain:

$$\boxed{\Delta H_P\,(ft\ fluid) = \frac{1}{2g}(v_D{}^2 - v_S{}^2) + z_{GD} - z_{GS} + 2.31\ \frac{p_{GD}(psig) - p_{GS}(psig)}{SG}} \qquad [5\text{-}8]$$

z_{GD} and H_{GD} are respectively the gauge height and gauge pressure head on the discharge side of the pump. Similarly, z_{GS} and H_{GS} are respectively the gauge height and gauge pressure head on the suction side. The gauge heights z_{GD} and z_{GS} are taken with respect to a common reference plane (see Figure 5-1). The velocities are given by:

$$v(ft/s) = 0.4085\ \frac{q(USgal/\mathrm{min})}{(D(in))^2}$$

Remember that the pressure at the pump inlet may be negative, so that a gauge capable of measuring negative pressure may be required.

As happens occasionally, we may not have the luxury of a pressure gauge on the suction side of the pump. However, we can calculate the pressure head at the suction, combined with the pressure measurement at the discharge, we can determine the Total Head of the pump.

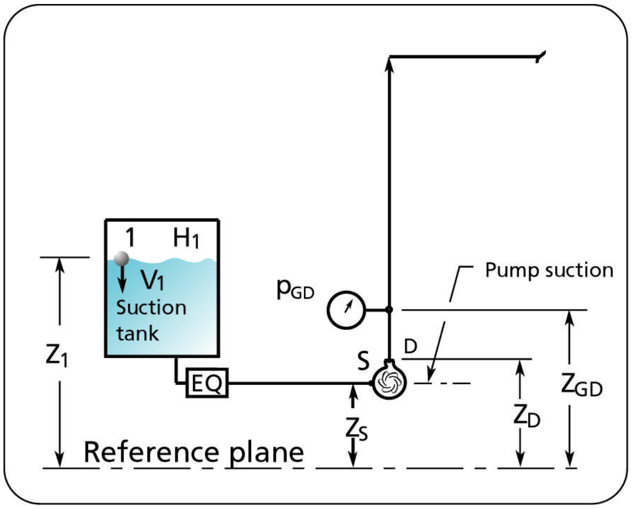

Figure 5-2 Measuring Total Head with only one gauge on the discharge side of the pump.

The head at point S (see chapter 3, equation [3-6]) is:

$$\bar{E}_S = H_S + \frac{v_S^2}{2g} \tag{5-9}$$

H_S is given in chapter 3 (see equation [3-4] as:

$$H_S = -(\Delta H_{F1-S} + \Delta H_{EQ1-S}) + \frac{(v_1^2 - v_S^2)}{2g} + (z_1 - z_S + H_1) \tag{5-10}$$

By replacing equation [5-10] into equation [5-9] we obtain:

$$\bar{E}_S = -(\Delta H_{F1-S} + \Delta H_{EQ1-S}) + \frac{v_1^2}{2g} + (z_1 - z_S + H_1) \tag{5-11}$$

The Total Head is given by:

$$\Delta H_P = \bar{E}_D - \bar{E}_S \tag{5-12}$$

where the head at the discharge $\overline{E}_D$ is:

$$\overline{E}_D = H_D + \frac{v_D^{\,2}}{2g} + z_D - z_S \qquad [5\text{-}13]$$

Therefore

$$\Delta H_P = \overline{E}_D - \overline{E}_S = H_D + \frac{v_D^2}{2g} + z_D - z_S + \Delta H_{F1-S} + \Delta H_{EQ1-S} - \frac{v_1^{\,2}}{2g} - (z_1 - z_S + H_1) \qquad [5\text{-}14]$$

H_D is given by equation [5-6] and inserted into equation [5-14]:

$$\Delta H_P = 2.31\frac{p_{GD}(psig)}{SG} + z_{GD} - z_D + \frac{v_D^2}{2g} + (z_D - z_S) + (\Delta H_{F1-S} + \Delta H_{EQ1-S}) - \frac{v_1^{\,2}}{2g} - (z_1 - z_S + H_1)$$

which after simplification becomes:

$$\boxed{\Delta H_P = 2.31\frac{p_{GD}(psig)}{SG} + z_{GD} - z_1 + \frac{v_D^2}{2g} + \Delta H_{F1-S} + \Delta H_{EQ1-S} - \frac{v_1^{\,2}}{2g} - H_1} \qquad [5\text{-}15]$$

5.2 NET POSITIVE SUCTION HEAD AVAILABLE (N.P.S.H.A.)

By definition, the NPSH available is the specific energy or head at the pump suction in terms of feet of fluid absolute, minus the vapor pressure of the fluid. If there is a pressure gauge on the suction side of the pump, as in Figure 5-1, then the head at point S is (see equation [3-6]):

$$\overline{E}_S = H_S + \frac{v_S^{\,2}}{2g} \qquad [5\text{-}16]$$

The value of H_S is given by equation [5-7] and by substitution into [5-16] we obtain:

$$\overline{E}_S = 2.31\,\frac{p_{GS}\,(psig)}{SG} + z_{GS} - z_s + \frac{v_S^2}{2\,g} \qquad [5\text{-}17]$$

Since *N.P.S.H.* is in feet of fluid absolute, the value of the barometric pressure head must be added to $\overline{E}_S$ and the vapor pressure of the liquid (H_{va}) is subtracted to get the *N.P.S.H.* available.

$$NPSH_{avail}\,(\,ft\ fluid\ absol) = \overline{E}_S + H_B - H_{va} \qquad [5\text{-}18]$$

By substituting equation [5-17] into [5-18] we obtain:

$$N.P.S.H.\,avail(\,ft\ \ fluid\ \ absol.) \;=\; 2.31\ \frac{p_{GS}\,(psig)}{SG} + z_{GS} - z_{s} + \frac{v_S^2}{2\,g} + H_B - H_{va} \qquad [5\text{-}19]$$

Or if the barometric and vapor pressure heads are available in terms of pressure, then:

$$NPSH_{avail}\ (\,ft\ fluid\ absol.\,) = 2.31\,\frac{p_{GS}(\,psi\,)}{SG} + \frac{v_S^{\;2}}{2g} + z_{GS} - z_S + 2.31\,\frac{(p_B - p_{va})}{SG} \qquad [5\text{-}20]$$

What is the difference between the N.P.S.H.A. of equation [5-19] vs the N.P.S.H.A. of equation [3-10] developed in chapter 3 which is restated here below:

$$N.P.S.H._{avail.}(ft\ \ fluid\ absol.) = -\,(\Delta H_{F1-S} + \Delta H_{EQ1-S}) + \frac{v_1^{\;2}}{2g} + (z_1 - z_S + H_1) + H_B - H_{va}$$

The main difference is that we are measuring the pressure at the suction instead of calculating it. When calculating the pressure we have to take into account the friction loss between points 1 and S as well as the elevation difference. When we measure the pressure, the result of this measurement includes the friction losses and the elevation difference since it is these energy sources which produce the pressure energy that is measured. Why is the velocity head required in equation [5-20], but not in equation [3-10]? Because the velocity head is an important energy source that is not included in the pressure measurement. In equation [3-10] the velocity energy was considered but cancels out during the development of the equation so that it does not appear in equation [3-10].

5.3 SHUT-OFF HEAD

To measure the shut-off head, at least one pressure gauge is required between the pump discharge flange and the discharge valve (see Figure 5-3). If possible, a gauge should be installed on the suction side of the pump, close to the inlet.

Measuring shut-off head is the same as measuring total head except that there is no flow through the pump.

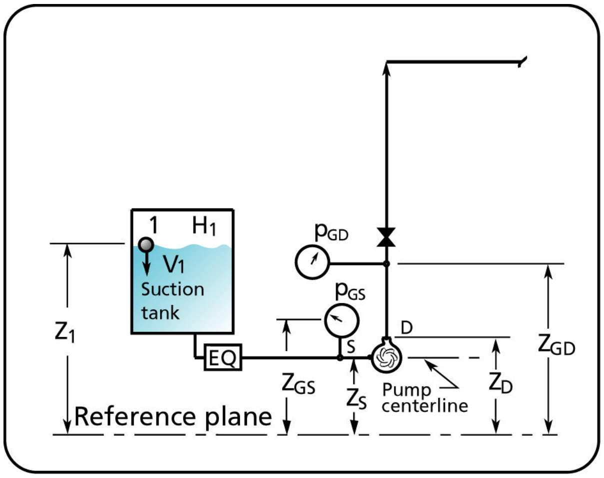

Figure 5-3 Measurement of the shut-off head.

Case 1. Pressure gauge NOT AVAILABLE on suction side of pump

We dealt with this case when we measured the total head with only one pressure gauge on the discharge side, the value for Total head is given by equation [5-15].
Since by definition there is no flow through the system when measuring shut-off head then $v_D = v_1 = 0$, and $DH_{F1\text{-}S} = DH_{EQ1\text{-}S} = 0$ therefore equation [5-15] becomes:

$$\Delta H_P = 2.31 \frac{p_{GD}(psig)}{SG} - (z_{GD} - z_1) - H_1 \qquad [5\text{-}21]$$

Case 2. Pressure gauge AVAILABLE on suction side of pump

When a pressure gauge on each side of the pump is available, then the shut-off head is given by the same equation as the total head (see equation [5-8]):

$$\Delta H_P\,(ft\ fluid) = \frac{1}{2g}(v_D^{\,2} - v_S^{\,2}) + z_{GD} - z_{GS} + 2.31\,\frac{p_{GD}(psig) - p_{GS}(psig)}{SG}$$

And since there is no fluid movement, v_S and $v_D = 0$, therefore equation [5-8] becomes:

$$\Delta H_P\,(ft\ fluid) = z_{GD} - z_{GS} + 2.31\,\frac{p_{GD}(psig) - p_{GS}(psig)}{SG} \qquad [5\text{-}22]$$

5.4 EQUIPMENT HEAD DIFFERENCE

The difference in pressure head between the outlet and the inlet of the equipment is:

$$\Delta H_{EQ} = H_4 - H_3 \qquad [5\text{-}23]$$

where H_3 and H_4 are respectively the pressure heads at points 3 and 4.

Case 1. Pressure gauges on each side of the equipment

The pressure measured with the gauge at point 3 must be corrected for the height difference between the gauge vertical position and the position of point 3.

$$H_3 = \frac{2.31\,p_3}{SG} + z_{G3} - z_3 \qquad [5\text{-}24]$$

The same is true for the pressure measured at point 4.

$$H_4 = \frac{2.31\,p_4}{SG} + z_{G4} - z_4 \qquad [5\text{-}25]$$

The difference in pressure head is then:

$$\boxed{\Delta H_{EQ} = H_4 - H_3 = \frac{2.31\,(p_4 - p_3)}{SG} + z_4 - z_3 + z_{G4} - z_{G3}} \qquad [5\text{-}26]$$

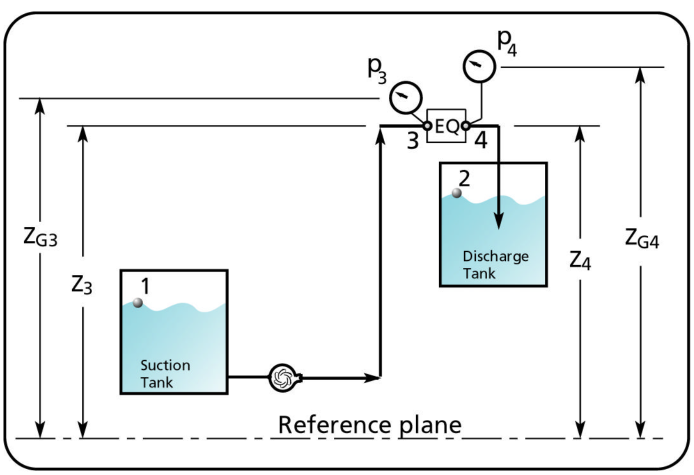

Figure 5-4 Gauge locations for equipment pressure head measurement.

Case 2. Pressure gauge on one side of the equipment only

Let us assume there is only one pressure gauge available, gauge p_3. H_3 is given by:

$$H_3 = \frac{2.31\,p_3}{SG} + z_{G3} - z_3 \qquad [5\text{-}27]$$

H_4 is determined by the method developed in chapter 2, which gives the pressure head anywhere within a system.

$$H_4 = \Delta H_{F4-2} + \Delta H_{EQ4-2} + \frac{(v_2^{\,2} - v_4^{\,2})}{2g} + z_2 + H_2 - z_4 \qquad [5\text{-}28]$$

By substituting equation [5-28] and [5-27] into [5-23], we obtain:

$$\boxed{\Delta H_{EQ} = H_4 - H_3 = \Delta H_{F4-2} + \Delta H_{EQ\,4-2} + \frac{(v_2^{\,2} - v_4^{\,2})}{2g} + z_2 - z_4 + H_2 - \frac{2.31\,p_3}{SG} + z_{G3} - z_3} \qquad [5\text{-}29]$$

5.5 FLOW MEASUREMENT

The measurement of flow rate is not always an easy task. Rarely, is there an accurate flow measurement device on the pipe which we are interested in. It is sometimes possible (without incurring a great expense) to measure flow by measuring the rate at which the discharge reservoir is filled, or a suction tank is emptied. The measurement volume, or the time of the measurement, should be small to avoid influencing the total head of the pump and therefore causing flow variations. In the event that this should prove impossible or impractical, measuring the current supplied to the pump motor is a method of establishing the power absorbed at the pump shaft. If we know the Total head (ΔH_P), then we can calculate the flow by using equation [5-31]. This is an indirect way of measuring flow. Because several errors may accumulate, this should only be used as verification of another measurement. Also, be aware that the motor characteristics such as power factor and efficiency must be known at the operating load.

A final word of caution. Any measurements deduced from data extracted from the pump curve assume that the pump is in good working condition (for example, proper clearance between impeller and casing, no excessive wear, etc.). This is of course not always the case.

5.6 CALCULATING FLOW BASED ON POWER CONSUMED BY THE MOTOR

Total Head (ΔH_P) and pump flow (q) in an existing system are measurable quantities. However, sometimes one of these terms may be difficult to determine. Why? The devices required for the measurements may be difficult to install and/or be expensive, or the equipment may not be shut down long enough to install the devices. However, the power consumed by the motor can be easily measured based on the current flow (ampères).

The power consumed by the pump (at the pump shaft) is:

$$\boxed{P_{pump}(hp) = \frac{SG \quad \Delta H_P\,(ft\ fluid) \quad q\,(US\,gal/\mathrm{min})}{3960 \quad h_{pump}}} \qquad [5\text{-}30]$$

where P_{pump} : power consumed at the pump shaft;
SG : specific gravity of the fluid;
DH_P : Total Head;
q : flow through pump;
h_{pump} : pump efficiency.

The power delivered to the pump shaft based on the flow of current to a 3-phase motor is:

$$\boxed{p_{pump}(hp) = \frac{1.34}{1000}\sqrt{3} \;\; V(volt) \;\; A(amp) \;\; h_{motor} \;\; P.F.} \qquad [5\text{-}31]$$

where V : motor supply voltage, usually 575 volts;
A : motor supply amperage;
h_{motor} : motor efficiency;
$P.F$.: power factor.

An induction motor has a reactive component in its magnetic filed that does not participate in any useful work. Therefore, we need to apply a power factor to the overall power to obtain the real power consumed. The power factor and motor efficiency is given by the motor manufacturers in the form of tables for various loads and different motor sizes (see Appendix E).

Note: the constant $\sqrt{3}$ is required for three-phase motors.

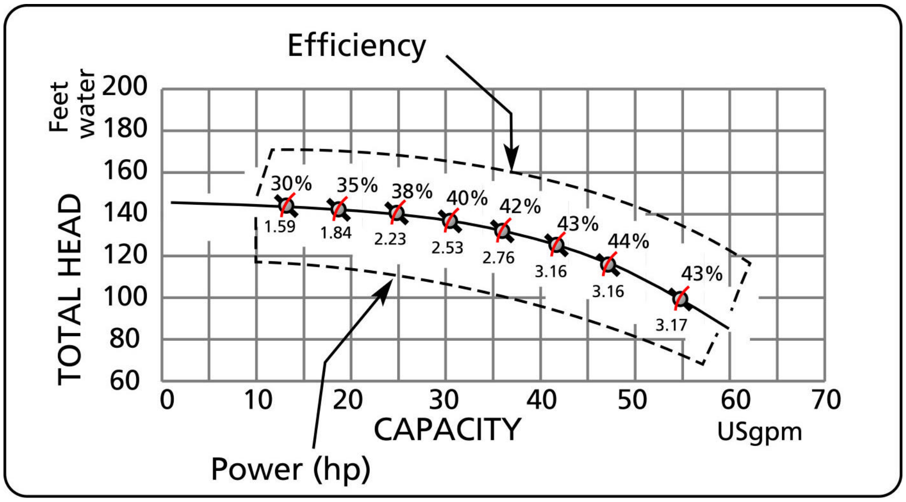

Figure 5-5 Locating the operating point by measuring the current.

Therefore, if we measure the current at the motor, we can calculate the power consumed by the pump. The power consumed depends on the flow, the head, and the efficiency of the pump. These three variables are available on the pump performance curve and define the operating point. So that if we know the power consumed by the pump, we can obtain the head, the flow, and the efficiency from the performance curve (see Figure 5-5).

Total Head can be measured by installing pressure gauges at the outlet and inlet of the pump. We can do without the inlet pressure measurement if the pressure can be easily calculated at this point. For example, if the pump suction is large and short and the inlet shut off valve is fully open and is of a design that offers little restriction, we can assume that the pressure head at the inlet of the pump is equal to the static head.

Tables of power factor and motor efficiency for standard induction motors are available from the major manufacturers. A table for ABB Premium Efficiency induction motor power factors and efficiency values is presented in Appendix E.

What is the best way to measure flow?

1. *If there is a good reliable flow transmitter in the line the problem is solved. Usually there is no such luck.*

2. *If you can measure the geometry of the discharge tank and you can get an operator to allow the tank to fill during a short period, you will be able to calculate the flow. This is probably the best method.*

3. *I have tried ultrasonic devices, which provide a non-invasive method of measuring flow. There are currently two types: transit time and Doppler. The Doppler requires particles in the fluid to measure the velocity. I have found it to be unreliable and imprecise. The transit time device requires little or no particles in the fluid and is quite precise when it registers a reading.*

The Hydraulic Institute has an excellent section on how to measure flow in their Standards book (see reference 1).