DIAPHRAGM TANK CALCULATION

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INTRODUCTION

Many booster applications are used for feeding water to consumers with varying consumption, meaning that the water flow varies significantly throughout the day. During these variations, the booster needs to keep the desired pressure. Depending on the booster design, this means that only one pump is active during low consumption and low flow, which leads to low efficiency. To overcome low-efficiency conditions, you can apply a start/stop operation. However, this requires a diaphragm tank to maintain the pressure when all the pumps stop.

When the pumping station is in operation, the diaphragm tank charges, and when it stops, it is discharged (see Figure 1). The pressure of the diaphragm tank changes just slightly during the charging and recharging phases. Thus, the pressure remains at an almost constant level during start/stop operation. The design of the diaphragm tank controls the number of starts and stops and determines the pressure variations between the starts and stops.

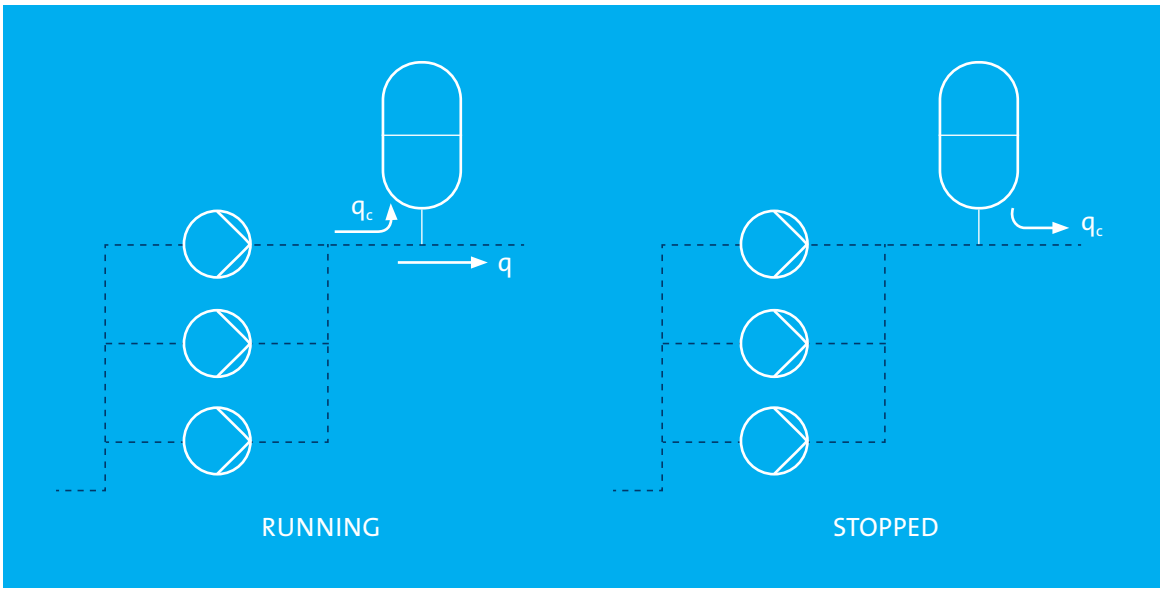

Figure 1: Charging and discharging of the diaphragm tank during start-stop operation. Here q_c is the charging-discharging flow of the diaphragm tank, and q is surplus flow fed to the network when the pumping station is running.

DIAPHRAGM DESIGN METHOD

During start-stop operation, charging can be controlled by slightly increasing the pumping station's pressure reference. When a new pressure reference is reached and the pumping station stops, the tank charges. The discharge can be controlled by supervising the pressure until it is slightly below the pressure reference and the pumping station restarts (see Figure 2). Along with the flow, the size of the tank defines the charging and the discharging time, also shown in Figure 2, and thereby the number of expected starts.

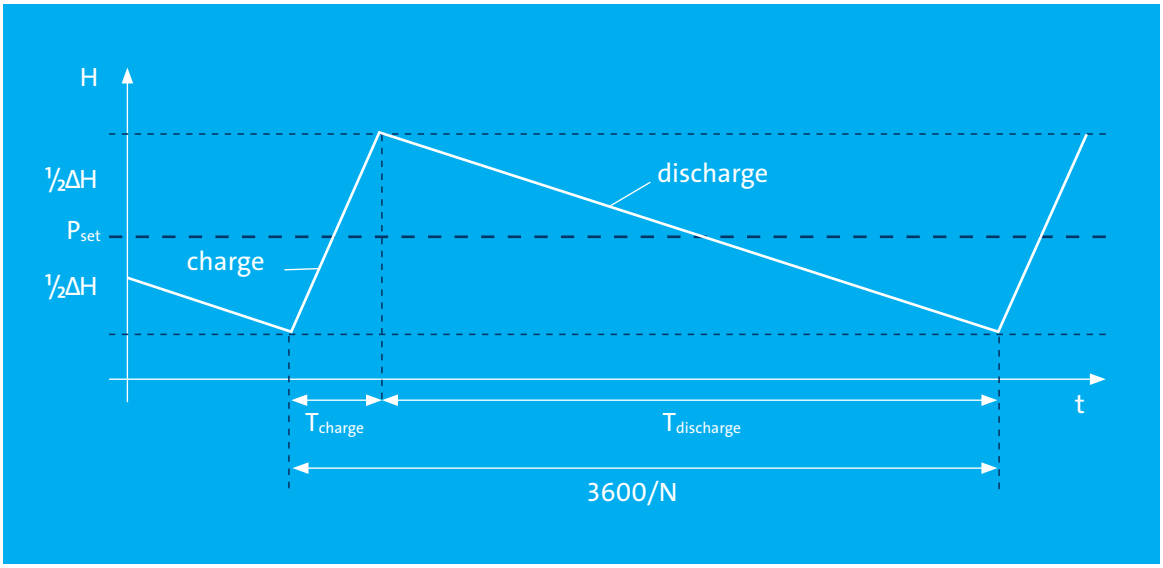

Figure 2: Charging and discharging pressure settings and tank pressure behaviour during charging and discharging.

Start-stop operation is initiated at a predefined minimum flow, as shown in Figure 3, along with the pressure variations. The worst-case scenario, which corresponds to the highest number of charge-discharge cycles over a time frame, is when the flow is just below the flow at which start-stop operation is initiated. We design the diaphragm tank based on these operating conditions.

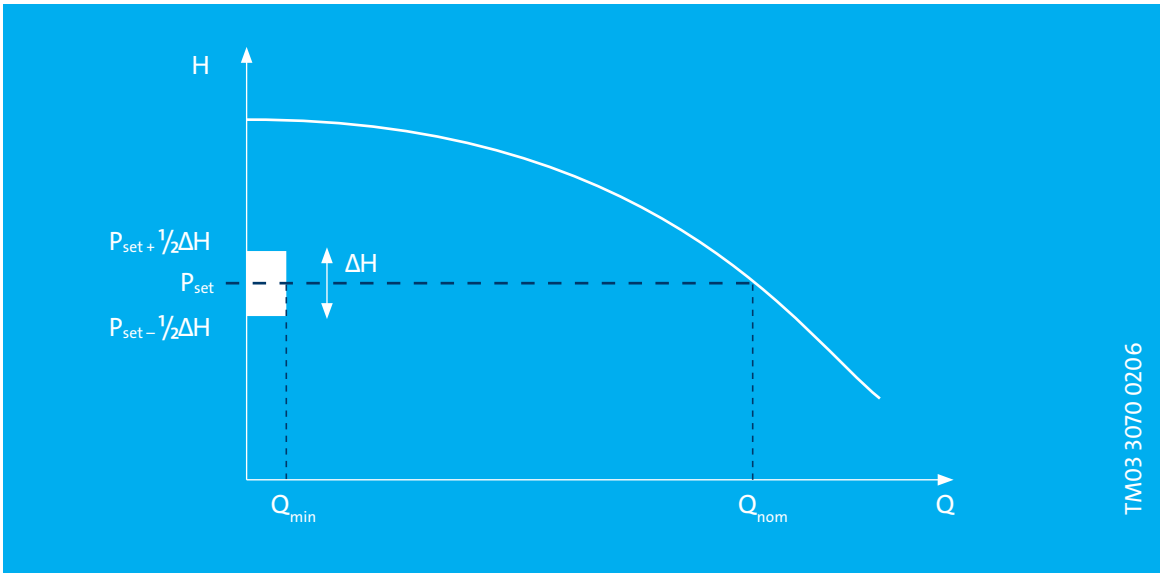

Figure 3: Pressure variation and flow definitions together with the pump curve of the pump type in the booster.

Therefore, the parameters needed for the design are:

Parameter	Unit	Symbol	Values
Nominal flow rate of the pump type.	m^3/h	Q	According to nameplate
Pressure setpoint of the booster station.	bar (relative pressure)	P_{set}	Setpoint of the system
Number of starts per hour.	-	N	Maximum starts allowable according to the pump specification. e.g., 200
The flow factor of the nominal flow, where the on/off operation starts **$Q_{min}=k_Q Q$.**	-	k_Q	2-10% depending on pump size.
On/off band factor of the pressure setpoint **$\Delta H = k_f P_{set}$**	-	k_H	10-25% depending on the setpoint and application
Factor of the pressure setpoint to pre-pressure the diaphragm tank. **The pre-pressure $k_f P_{set}$ must always be lower than the setpoint P_{set} pressure minus the hysteresis ΔH/2**	-	k_f	70 % in speed-regulated systems
Time to charge the tank	sec	T_{charge}	10 seconds. See the appendix for more advanced calculations.

Based on these design values, the tank volume is calculated by

$$V_0 = \frac{k_Q\, Q(P_{set}+1)^2 \left(\frac{3600}{N} - T_{charge}\right)}{3.6\, k_H\, P_{set}(k_f\, P_{set}+1)} \qquad (1)$$

We've calculated the tank size during a worst-case scenario, which typically doesn't last too long. The number of starts will normally be lower than the design values, and therefore, you can obtain a robust design by applying the calculation in (1).

EXAMPLE

The design methods proposed by (1) are exemplified in the following table. We'll show the provided examples used to calculate the volume of the diaphragm tank for a different number of starts per hour (30 and 200 starts/hour).

Parameter	Unit	Symbol	Values
Nominal flow rate of the pump type.	m^3/h	Q	10
Pressure setpoint of the booster station.	bar (relative pressure)	p_{set}	4
Number of starts per hour.	-	N	30 / 200
The flow factor of the nominal flow, where the on/off operation starts **$Q_{min}=k_Q\, Q$.**	-	k_Q	0.1
On/off band factor of the pressure setpoint **$\Delta H=k_H\, P_{set}$.**	-	k_H	0.2
Factor of the pressure setpoint to pre-pressure the diaphragm tank. **The pre-pressure $k_f\, p_{set}$ must always be lower than the setpoint pressure minus the hysteresis ΔH/2**	-	k_f	0.7
Time to charge the tank	Sec	T_{charge}	10
Diaphragm tank volume.	l	V_0	251 / 18.3

Using N = 30 starts per hour, and using the formula (1), the volume becomes

$$V_0 = \frac{k_Q\, Q(P_{set}+1)^2 \left(\frac{3600}{N} - T_{charge}\right)}{3.6\, k_H\, P_{set}\,(k_f\, P_{set}+1)} = \frac{0.1 \cdot 10 \cdot (4+1)^2 \left(\frac{3600}{30} - 10\right)}{3.6 \cdot 0.2 \cdot 4 \cdot (0.7 \cdot 4 + 1)} = 251\ [l]$$

Increasing the number of starts per hour to 200 leads to

$$V_0 = \frac{k_Q\, Q(P_{set}+1)^2 \left(\frac{3600}{N}\ T_{charge}\right)}{3.6\, k_H\, P_{set}\,(k_f\, P_{set}+1)} = \frac{0.1 \cdot 10 \cdot (4+1)^2 \left(\frac{3600}{200} - 10\right)}{3.6 \cdot 0.2 \cdot 4 \cdot (0.7 \cdot 4 + 1)} = 18.3\ [l]$$

APPENDIX: DERIVATION OF THE DESIGN MODEL

A diaphragm tank is installed between the pump and the network as a buffer during low flow operation. This buffer makes it possible to run the pumping station in on/off mode, ensuring that the pump does not operate at too low a flow. See a sketch of a diaphragm tank in Figure 1. Here, V_o is the volume of the diaphragm tank, V_a is the part of the volume filled with air, and V_w is the part filled with water. Note that the split between V_a and V_w will change according to the changing pressure.

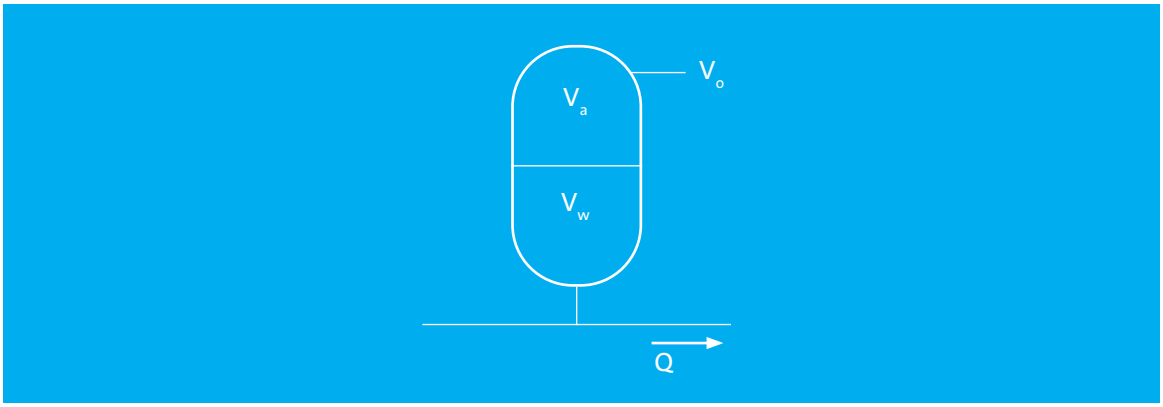

Figure 4: Sketch of a diaphragm tank. V_0 is the volume of the diaphragm tank, which is split between an air volume V_a and a water volume V_W.

The relation between the air volume V_a and the pressure p is described by the ideal gas law

$$pV_a = nRT$$

where n is the amount of substance, R is the ideal gas constant, and T is the temperature of the gas. We assume that the dynamic changes of the pressure and the thermal connection to the surroundings are such that gas temperature is constant, hence C=nRT is a constant.

From the diaphragm tank sketch in Figure 1, the volume of gas $V_a = V_0 - V_w$, so the ideal gas equation of the diaphragm tank becomes

$$p(V_0 - V_w) = C \tag{A1}$$

At the point of installation, the diaphragm tank is pre–pressurised with a pressure p_0. Under these conditions, the water volume is $V_w = 0$, meaning that

$$p_0 V_0 = C \tag{A2}$$

The two expressions for C in (A1) and (A2) lead to

$$pV_0 - pV_w = p_0V_0 \iff V_w = \frac{(p - p_0)V_0}{p} \tag{A3}$$

The pump operates in such a way that the pressure is boosted to a stop the pressure value $\overline{p}$ ($\overline{p} > p_0$). Then, the pump stops until the pressure reaches the start pressure value $\underline{p}$ ($\overline{p} > \underline{p} > p_0$), at which point the pump starts. The change of volume between the stop and start pressure is denoted as ΔV_w and can be expressed using (A3)

$$\Delta V_w = \frac{(\overline{p} - p_0)V_0}{\overline{p}} - \frac{(\underline{p} - p_0)V_0}{\underline{p}} = \frac{\underline{p}(\overline{p} - p_0)V_0 - \overline{p}(\underline{p} - p_0)V_0}{\overline{p}\underline{p}} = \frac{(\overline{p} - \underline{p})p_0V_0}{\overline{p}\underline{p}} \tag{A4}$$

The start and stop values are often defined by a setpoint pressure value p_s and a variation of this pressure value δp. Using p_s and δp, the relation between the start and stop values are expressed by

$$\overline{p} = p_s + \delta p \quad , \quad \underline{p} = p_s - \delta p$$

Introducing these expressions for the start and stop pressures into (A4) leads to

$$\Delta V_w = \frac{(p_s + \delta p - p_s + \delta p)\, p_0V_0}{(p_s + \delta p)(p_s - \delta p)} = \frac{2\delta p p_0 V_0}{p_s^2 - \delta p^2} \iff \Delta V_0 = \frac{(p_s^2 - \delta p^2)\,\Delta V_w}{2\delta p p_0} \tag{A5}$$

The volume flow for the system is denoted Q. It is demonstrated in Figure 1. The off-time or discharge time $T_{discharge}$ denotes the pump-off-time between the start and stop pressures. Now, define the number of starts per hour as N, and the time between starts is given as 3600/N. The time between starts is divided between a charging time T_{charge}, in which the tank is filled, and a discharging time $T_{discharge}$, in which the tank is emptied (See Figure 2.)

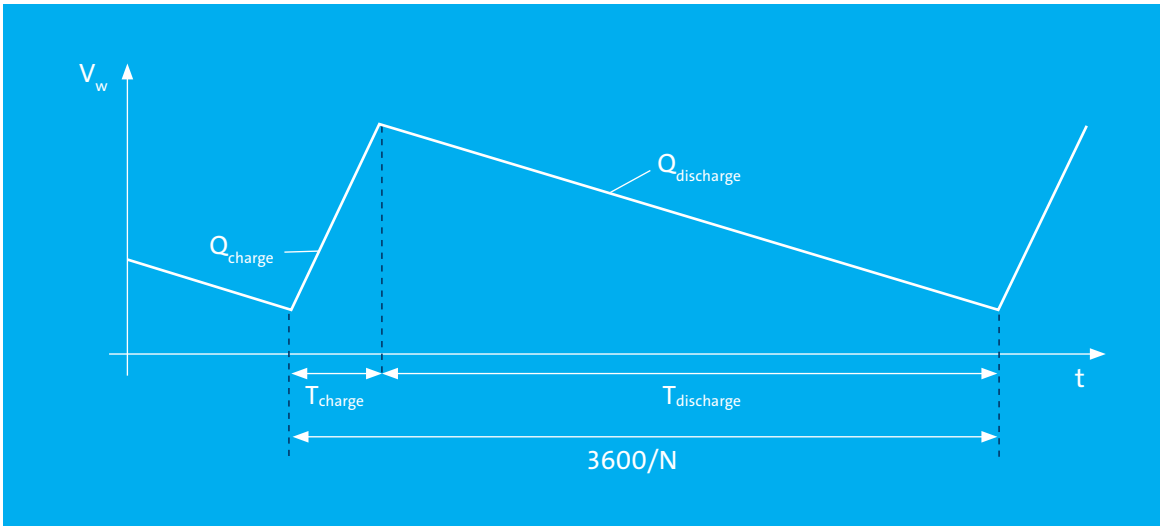

Figure 5: Volume versus charging and discharging of the diaphragm tank.

The flow at discharge is defined as a fraction of the nominal flow so that

$$Q_{discharge} = s_Q\, k_Q\, Q \tag{A6}$$

Here, $Q_{discharge}$ is the discharge flow in [m^3/sec] when the pump stops, k_Q is the scaling of the average flow Q to obtain the discharge flow, and s_Q scales the flow from the unit used for Q to the IS unit [m^3/sec].

The charging flow $Q_{discharge}$ varies between the pump flow when the pump is running and the $Q_{discharge}$. Assuming the consumption is the same during charging and discharging of the tank and that the pump flow during charging equals the nominal flow Q, the charging flow is given by

$$Q_{discharge} = s_Q\, Q - Q_{discharge} = s_Q\,(1 - k_Q)Q \tag{A7}$$

In which the pump flow in the same units as the discharge flow is $s_Q Q$. We chose to calculate the active volume of the tank ΔV_w using the discharge flow and the discharge time. The discharge time from Figure 2 is

$$T_{discharge} = \frac{3600}{N} - T_{discharge} \tag{A8}$$

The charged and discharged is the same, meaning that

$$\Delta V_w = Q_{\text{-discharge}} T_{\text{discharge}} = Q_{\text{-charge}} T_{\text{-charge}}$$

Here, volume ΔV_w is the active volume of the tank and is given by (A5). Using (A6) and (A7) relating to the charge and discharge flows, respectively, and the relation between the charge and discharge time in (A8), the following link is obtained:

$$s_Q k_Q Q\left(\frac{3600}{N} - T_{\text{discharge}}\right) = s_Q (1 - k_Q)\, Q T_{\text{charge}} \quad <=> \quad T_{\text{discharge}} = k_Q \frac{3600}{N} \tag{A9}$$

Often, T_{charge} is chosen as a fixed number. Using (A6) and (A8), the following expression for the volume ΔV_w is obtained

$$\Delta V_w = Q_{\text{discharge}} T_{\text{discharge}} = \left(\frac{3600}{N} - T_{\text{discharge}}\right) s_Q k_Q Q \tag{A10}$$

Here, Q_{min} is the flow in [m³/sec], and ΔV_w is the active volume of the tank in [m³], k_Q is the scaling of the average flow Q to obtain the minimum flow, and s_Q scales the flow from the unit used for Q to the IS unit [m³/sec], meaning that $s_Q = 1/3.6$.

The pressure p_s is the absolute pressure setpoint, and δp is the deviation from this setpoint pressure in SI units. In practice, the pressure setpoint is given as a relative pressure p_{set} in the unit [bar], and likewise, the pressure band between the minimum and maximum pressure ΔH is given in the unit [bar]. This leads to the following expressions for p_s and δp

$$p_s = s_p\,(P_{\text{set}} + 1) \quad , \quad \delta p = s_p \frac{\Delta H}{2} = s_p \frac{k_H P_{\text{set}}}{2} \tag{A11}$$

where k_H is the fraction of the setpoint that is used as the pressure band and s_p scales form [bar] to the IS unit [pa].

The absolute preset pressure p_o of the diaphragm tank is defined by a fraction of the setpoint pressure P_{set}. For this, we use the fraction term k_f. By using this, the following expression gives the preset pressure of the diaphragm tank:

$$p_0 = s_p\,(k_f P_{\text{set}} + 1) \tag{A12}$$

The expression in (A10), (A11), and (A12) defines the variables on the right-hand side of (A5), meaning that these values are needed to calculate the volume of the diaphragm tank. Introducing (A10), (A11), and (A12) in (A5) leads to

$$V_0 = \frac{(s_p{}^2 (P_{set}+1)^2 - (s_p k_H P_{set})^2/4)\, s_Q \left(\frac{3600}{N} - T_{discharge}\right) k_Q Q}{s_p k_H P_{set}\, s_p (k_f P_{set}+1)}$$

$$= \frac{k_Q Q ((P_{set}+1)^2 - (k_H P_{set})^2/4) \left(\frac{3600}{N} - T_{discharge}\right)}{k_H P_{set} (k_f P_{set}+1)}$$

in practical cases, $0<(k_H{}^2)/4\ll 1$. Therefore, the second term of the first parenthesis $(k_H P_{set})^2/4$ is much less than the first term $(P_{set}+1)^2$, meaning that the second term often is neglected. Ignoring this second term leads to the final expression for calculating the tank volume

$$V_0 = s_Q \frac{k_Q Q (P_{set}+1)^2 \left(\frac{3600}{N} - T_{discharge}\right)}{k_H P_{set} (k_f P_{set}+1)} \qquad \text{(A13)}$$

which corresponds to (1). Therefore, this can be used for tank designs when the charging time T_{charge} is known. When the charging time is unknown, you can calculate it using (A9), which leads to the following tank volume

$$V_0 = s_Q \frac{k_Q Q (P_{set}+1)^2 \left(\frac{3600}{N} - k_Q \frac{3600}{N}\right)}{k_H P_{set} (k_f P_{set}+1)} = s_Q \frac{3600}{N} \frac{k_Q (1-k_Q) Q (P_{set}+1)^2}{k_H P_{set} (k_f P_{set}+1)} \qquad \text{(A14)}$$

which and can be used as an alternative to (1) when the charge time T_{charge} is unknown. Thus, you can use it for tank designs with an unknown charging time T_{charge}.

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