Chapter 4: Theoretical background for the hydraulic system

Theoretical information on the design of a hydraulic system is provided in this chapter. An overview of Bernoulli's equation to determine pump power is given in section 4.1. Frictional losses are discussed in the next part and properties of selected materials are finally discussed.

4.1 Bernoulli's equation

The equation proposed by Daniel Bernoulli in 1738 relates pressure, distance and velocity differentials between two points in the path of a moving fluid. The most general form of the equation [Foust *et al.*, 1961] is:

$$P_1 + \frac{1}{2}\rho V_1^{\,2} + \rho g z_1 = P_2 + \frac{1}{2}\rho V_2^{\,2} + \rho g z_2 \qquad \text{(Eq. 4-1)}$$

Where

P_1= **pressure at point 1 (Pa)**

P_2= **pressure at point 2 (Pa)**

V_1= **velocity at point 1 (m/s)**

V_2= **velocity at point 2 (m/s)**

z_1= **height at point 1 (m)**

z_2= **height at point 2 (m)**

ρ = **density of the fluid (kg/m^3)**

g= **gravity acceleration, 9.81 (m/s^2)**

The first term in each side refers to hydrostatic pressure, the second to kinetic energy and the third to potential energy. If Bernoulli's equation is rearranged multiplying it by volume, density is replaced by mass and the pressure is replaced by work. This equation can be applied assuming:

a. Steady flow.
b. Incompressible liquid (steady density).
c. Non-viscous fluid.
d. There is no friction.

The form of Bernoulli's equation used to obtain the power needed for a pump [Foust *et al.*, 1961] is the following:

$$W_P = M\left[\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2\alpha g_c} + \frac{g(z_2 - z_1)}{g_c} + E_f\right] \qquad \text{(Eq. 4-2)}$$

Where

M = **mass flow rate (kg/s)**

α = **velocity correction factor (dimensionless)**

g_c = **unit correction parameter (kg m/N s^2)**

Ef= **energy losses due to friction (N m/kg)**

In the latter form, energy loss due to friction is accounted for, but the other assumptions remain.

4.2 Energy loss due to friction

A combination of methods was used, the Darcy friction factor and the K factor to account for the term E_f [Foust, 1961]. There are six point sites, that added up form the total energy loss due to friction;

$$E_{f_{Total}} = Inlet + Outlet + Piping + Accessories + Contractions + Expansions$$

For the inlet, outlet, contractions and expansions, the K method (Eq. 4-3) was used. For accessories and piping, the Darcy friction factor (Eq 4-4) was used.

$$E_f = K\left(\frac{V^2}{2\alpha g_c}\right) \qquad \text{(Eq. 4-3)}$$

$$F_D = \left(\frac{L}{D}\right) * \left(\frac{V^2}{2\alpha g_c}\right) \qquad \text{(Eq. 4-4)}$$

Where

L=**pipe's longitude (m)**

D=**pipe's internal diameter (m)**

F_D=**darcy's friction factor (dimensionless)**

K = **K factor (dimensionless)**

4.3 Accessory materials

4.3.1 Metal

Metal is one of the most widely used materials in the industry. Up to the arrival of plastic in the mid 20th century, practically all piping, equipment and accessories were made of metal, pure or more frequently, alloyed. Nowadays, most equipment is still manufactured in metal, and most pipes and heavy duty accessories too. The most common used metals are steel, iron (in different purity grades), nickel, copper, aluminum, bronze, lead and titanium.

In the following sections, the most important properties of the metals used in building the pilot plant are depicted:

Cast iron

It is not a very strong or resistant material but it is often employed in the industry. Gray cast iron is cheap and easy to mould. It is constituted of approximately 1.7-4.5% C and it has Si, Mn and Fe. It absorbs vibration and is resistant to wear. However it is fragile and has little resistance to impact. It has a moderate resistance to corrosion, and to phosphoric, nitric, sand sulfuric acids. It tolerates some alkaline and caustic solutions [Perry, 1992].

Aluminum

Its thermal conductivity is about 60% than that of copper. Pure Al is used for heat transfer, and for electrical applications. It is easy to mold because of its softness and lightweight. It is recommended not to exceed 200°C for it becomes less resistant to traction. It is highly resistant to industrial vapors, brine, fresh water and concentrated nitric acid. Many mineral acids attack Al, and it shouldn't be used with strong caustic compounds. There are many alloys that have increased resistance to traction, but are generally more susceptible to corrosion [Perry, 1992]. Anodizing is the process of growing an oxide film over the surface of some metals by an electrochemical process. Anodized aluminum then has a thin oxide barrier. In certain acidic electrolytes it has an added thick oxide coating with high density microscopic pores. This coating increases its hardness, resistance to corrosion, and enables coloring to be added. The porous coating may be sealed with hot water to keep the dye within the structure and to provide smoothness to the surface [Alwitt, 2002].

Stainless steel

There are over 70 types of stainless steel standards and many special alloys. Generally they all have an iron base with 12-30% Cr, 0-22% Ni and small quantities of C, Nb, Cu, Mb, Se, Ta y Ti [Perry, 1992].

There are three groups of stainless steel alloys:

A) Martenitic alloys

They have 12-20% Cr, and controlled amounts of C, and other additives. They may be hardened by thermal treatment. Their resistance to corrosion is lower than for austenitic stainless steels and they are used in slightly corrosive environments (ambient, organic matter and fresh water) [Perry, 1992].

B) Ferritic alloys

They are 15-30% Cr with less than 0.1% C. They tolerate corrosion and may be hardened with cold treatment. Ferritic alloys are ductile and are easy to shape and mould. It is not recommended for reducing acids like HCl, but it can handle oxidative media and moderately corrosive substances [Perry, 1992].

C) Austenitic alloys

They have 16-26% Cr, 6-22% Ni and less than 0.08% C. They are the most resistant to corrosion, and are hard and ductile. This type of stainless steel is hardened by work and the addition of Mb increases its resistance to corrosion and punctures [Perry, 1992].

4.3.2 Plastics

In recent years plastics have become widely used in process plants. Due to some of their characteristics (light weight, chemical resistance, low cost, ability to be molded), they have replaced some of the traditionally metal accessories. Generally they are unsuitable to work with high temperatures or pressures, and their expansion coefficients are relatively high.

PVC

Polyvinyl chloride is a thermoplastic made up of the vinyl chloride monomer. PVC is a hard plastic that is made softer and more flexible by the addition of plasticizers, the most widely used being phthalates. The material is often used for pipelines in the water and sewer industries because of its inexpensive nature and flexibility [Wikipedia, 2005]. It is resistant to dilute and concentrated acids, alcohols, bases, aliphatic hydrocarbons and mineral oils. It is not recommended to be used with aldehydes, esters, ketones, aromatic and halogenated hydrocarbons [Wikipedia, 2005]. It can be used with temperatures up to 70°C (melting point is 80°C).

HDPE

High density polyethylene is a linear polymer derived from ethylene that has a high crystalline structure. The regular packing of atoms diminishes empty spaces, increasing the molecular weight. It is a rigid material that can be used above 100°C (melting point, approximately 135°C). It contracts and expands easily with temperature changes. It is resistant to dilute and concentrated acids, alcohols and bases, but its not recommended to be used with halogenated hydrocarbons and oxidizing agents.

CPVC

Chlorinated polyvinyl chloride is PVC that has been chlorinated via free radical chlorination reaction. The amount of chlorine in the material depends on the method of synthesis and may vary from 56.7 to 74% Cl. Most commercial resins have between 63 to 69% Cl. The more Cl in CPVC, the glass transition temperature increases [Wikipedia, 2005]. It is easily molded and has high-temperature (up to 93°C) and corrosion resistance. As PVC it can be kept clear or be pigmented and is fire resistant. CPVC shows an improved resistance to acids compared to PVC, and works well for bases too. Additionally it is apt for use with salts and aliphatic hydrocarbons. It is difficult to ignite and stops combustion once the flame is taken away. However, incineration of CPVC may produce dioxins, due to the high Cl content. When assembling pipes, special cement must be used to join CPVC parts [Wikipedia, 2005].

4.3.3 Glass

Glass is an inorganic product made of silicates that harden when cooled down. It has excellent resistance to acid except fluoric and concentrated hot phosphoric. Also, it may be attacked by concentrated hot alkaline solutions. The main disadvantage of glass is fragility and mechanical impacts or sudden changes in temperature easily crack it [Perry, 1992]. It is a transparent material and most radiation passes through it. Glass is easily molded and shaped, but cannot withstand high pressure or temperature. Borosilicate glasses are a family of glasses which contain boric oxide instead of iron oxide. Its approximate chemical composition is 70% silica, 10% boric oxide, 8% sodium oxide, 8% potassium oxide and 1% calcium oxide [Wikipedia, 2005]. Commercial brands vary their compositions according to different needs. This type of glass is very resistant to attack by water, acid, salt solutions, halogens and organic solvents [Beardmore, 2005]. It tolerates large thermal and mechanical shock. Borosilicate glass has good optical properties, with the ability to transmit light through the visible and near UV spectrum [Beardmore, 2005]. The most well known member of the borosilicate glass family is Pyrex®.