Energy consumption in pumps – friction losses

In this second article in a series on energy savings in pumps, Hans Vogelesang, director of Netherlands-based design consultancy PumpSupport, deals with some practical aspects of fluid mechanics. In particular, he looks at the influence of pipe diameter, bends and other features of piping systems on friction loss and energy consumption.

In the first article in this series, the concepts of geodetic differential head and possible pressure differences in the suction and discharge tanks were discussed. Together these determine the differential pressure to be delivered by a pump to ensure the required flow. However, the introductory article did not deal with the effects of friction losses, which will now be gone into more extensively.

Effects of friction losses

Friction losses refer to the difference in pressure needed to overcome the pressure drop during flow through pipes (Figure 1). Such losses only occur as a result of dynamic movement caused by flow; consequently, the pressure difference associated with this process is referred to as the dynamic differential pressure. Friction losses can only occur when flow actually takes place.

As was shown in the previous article, the pump must produce a sufficient difference in pressure to bridge the geodetic differential head and possible pressure differences in the tanks. This is known as the stationary differential pressure, referring as it does to the difference in pressure required for motionless fluids.

Once a fluid begins to flow through a pipe it will therefore be necessary to overcome the extra difference in pressure caused by friction losses. This will have to be provided by the pump, in addition to it overcoming the stationary differential pressure. The pump’s differential pressure will always be made up of the sum total of the stationary and dynamic differences in pressure.

As friction losses always represent an absolute energy loss, they need to be reduced as much as possible, if energy is to be saved. As explained previously, a 1 bar pressure difference at a 100 m³/h pump capacity ‘costs’ 4 kWh. A reduction in friction loss from 1 bar to 0.5 bar will result in the energy loss being reduced by 50%, thereby saving 2 kWh every hour. This is why it is possible to achieve significant savings, especially in (near) continuous operations (365 days per year, 24 hours per day = 8760 hours per year!).

What influences friction losses?

It is common knowledge that friction losses have a significant effect on our daily lives. For instance, we are all aware that cars need more energy and therefore more fuel at higher speeds than at low speeds. Luckily for us, car designers have already done a great deal to limit this: they have their designs tested in wind tunnels and try to reduce drag as much as possible by adapting the design. However, despite optimal designs, friction still occurs and increasingly so at higher speeds.

The velocity of the fluid is also of great influence in pipe flow. So, just as a car designer adapts the design to reduce drag, the pump system designer will have to do the same. How can this be achieved when testing in a wind tunnel is not an option?

Fortunately, much research into friction losses has already been done. This knowledge and experience has been laid down and published in handbook form. One example is the much-used Crane Technical Paper TP-410 entitled Flow of Fluids through Valves, Fittings and Pipe. This well-known English text...
gives the standardized method and details needed to calculate pressure loss resulting from flow in pipe systems.

Designers worldwide use Crane Technical Paper TP-410 as the standard work in the field of flow in pipes, valves and other in-line components such as bends and reducing pieces. It provides not only the theory, together with graphs and formulas, but also practical workplace examples and readily usable resistance factors. The latter are based on extensive testing and enable precise calculations to be made regarding which equipment to employ in a particular system. TP-410 was originally published in 1942. Nowadays, the more-recent editions are deemed to be essential reading for engineers, designers, researchers and students in all areas of technology that deal with pipe flow.

**Reducing friction loss**

In all cases of pipe flow a pressure difference is required to overcome friction loss.

Two factors play a part in the pressure difference. Firstly, there is the friction that results from the particles flowing along the rough inner pipe surface and from the difference in velocity of the individual particles. In the case of turbulent flow, the particles will additionally all be moving in different directions, causing extra turbulence losses. This is known as viscous friction and can be calculated using the Darcy-Weisbach equation (see Box 1). Secondly, there is the extra pressure difference required to produce a change in the flow (flow direction through bends and T-pieces, and acceleration through reducing pieces, non-return valves, etc.).

How these friction losses can be calculated is shown in detail in Box 1. Any such calculations will be affected by a large number of factors. If you wish to save energy then the friction losses must be kept as low as possible by selecting the most favourable conditions for any particular design.

A significant number of these conditions are, however, determined by the mechanics of the process and cannot be altered. For example, the volume and viscosity of the fluid to be transported are two factors that are largely pre-determined. Extremely viscous fluids could be heated beforehand, but the downside is the extra energy this would consume. However, in the case of fluids that need to be heated during the process anyway, it does make good sense to do this before pumping actually begins.

Equation 5 in Box 1 shows how friction losses can be reduced when the recommendations below are adhered to.

**Reduce pipeline length**

The length of a pipeline is crucial, as Equation 5 shows. Friction loss can be reduced by designing a system that significantly limits the transportation distance. Positioning a storage tank...
Box 1. Flow calculations for completely filled circular pipes

**Velocity calculation**
The following formula is used to work out the average velocity of a fluid:

\[ v = \frac{Q}{A} \]  

*Equation 1*

where \( v \) = velocity (m/s); \( Q \) = volume of flow (m³/s); and \( A \) = internal cross-sectional area of the pipe (m²).

**Friction loss calculation**
Friction loss is made up of two factors: the difference in pressure required to overcome the viscous friction and the difference in pressure required to change the kinetic energy at points of directional change (bends, etc.) and acceleration (reducing pieces, etc.).

a) The difference in pressure required to overcome the viscous friction can be calculated using the Darcy-Weisbach equation:

\[ \Delta p = \frac{\nu^2}{2} \left( \frac{fL}{d} \right) \]  

*Equation 2*

where \( \Delta p \) = pressure difference due to friction in N/m² (1 bar = 10⁵ N/m²); \( \rho \) = fluid density (kg/m³); \( \nu \) = velocity (m/s); \( f \) = friction factor (dimensionless number, also expressed as \( \zeta \)); \( L \) = pipe length (m); and \( d \) = pipe internal diameter (m).

The friction factor \( f \) can be determined from Moody's diagram (Figure 2) and is based on the Reynolds number and the relative roughness of the inside of a pipe.

The dimensionless Reynolds number, \( Re \), is calculated as follows:

\[ Re = \frac{\nu d}{\nu} \]  

*Equation 3*

where \( \nu \) = kinematic viscosity in m²/s (1 cSt = 10⁻⁶ m²/s); and \( \nu \) and \( d \) are as previously defined.

Because the Reynolds number is dependent on both viscosity and velocity, the friction factor will be mainly determined by the fluid's viscosity, the flow regime (laminar or turbulent) and the roughness of the inside of the pipe.

b) Using the following formula it is possible to calculate the extra difference in pressure required to produce a change in the flow (change of flow direction and/or velocity) in each separate component (bend, reducer, etc.):

\[ \Delta p_{extra} = \frac{\nu^2}{2} k \]  

*Equation 4*

where \( \Delta p_{extra} \) = extra difference in pressure (N/m²); \( k \) = resistance coefficient for a particular component (dimensionless number, also expressed as \( \zeta \)).

c) The total friction loss in a pipe that has several fittings, bends, attachments and the like is calculated using the formula below, by adding the pressure difference in Equation 4 to that caused by viscous friction:

\[ \Delta p = \frac{\nu^2}{2} \left( \frac{fL}{d} \right) + \sum k \]  

*Equation 5*

where \( \Delta p \) = total friction loss (N/m²); \( \sum k \) = the total of the resistance coefficients of all the bends, etc., and the other parameters are as previously defined.

Close to the system could result in the pipe length being halved, thereby cutting energy losses by 50%.

**Pipe diameter selection**

According to Equation 5, the fluid velocity will have a quadratic effect on friction losses, reducing friction loss by a quarter when the velocity is halved. The reverse will of course also apply: double the velocity and the differential pressure will increase fourfold. The designer should therefore concentrate on limiting the velocity in the pipe. Note that the rate should not be too low, as this would require the pipe diameter to be disproportionately large for a particular volume and the cost of the pipes unnecessarily high. In its *System Efficiency* handbook³, Europump recommends that when determining pipe diameter an energy-efficient choice should be based on the following criteria, which apply to fluids with a maximum viscosity of 100 centistokes (cSt) and a density ranging between 700 and 1200 kg/m³:

- **Discharge pipes:** velocity between 1.5 and 2.0 m/s;
- **Suction pipes:** velocity between 0.75 and 1.25 m/s.

By employing these design criteria it will be easy to select the correct pipe diameter for a specific volume of flow. Sticking to these recommendations will provide a number of benefits: not only will energy be saved but it will also result in other improvements, such as prevention of cavitation and vibration and reduced incidence of water hammer and erosion.

However, pump users should note that it will not generally be in the interests of contractors to fit an energy-efficient system. If it is left to them, a smaller pipe size will be installed for cost-cutting reasons, as all the shut-off valves, non-return valves and filters will then be cheaper too. This practice is diametrically opposed to the user’s interests, due to the increased friction losses and the correspondingly higher energy costs. It is therefore important when commissioning work to draw up clear and detailed specifications.

**Use hydraulically smooth pipes**

Moody’s diagram (Figure 2) shows that the friction factor for turbulent flow is determined by the Reynolds number and the relative roughness of the pipe. The relative roughness is the ratio between the actual roughness and the pipe diameter. For a given level of finish, the relative roughness will decrease as the pipe diameter increases, that is, the pipe becomes hydraulically smoother. Larger diameter pipes can therefore be made from concrete with a rough finish. Smaller diameter pipes should be made of materials with a smooth finish. It is important to take into consideration that the roughness will increase over the course of time due to corrosion, scale deposits, etc.

**Avoid short-radius elbows**

Using long-radius elbows will ensure that the differential pressure required to steer the direction of flow can be lower than when using sharp, right-angled connectors, such as elbow joins or Y-pattern T-pieces that are welded together at right angles. As the radius is increased, the resistance coefficient (\( k \) or \( \zeta \)) caused by the bend will be reduced. Avoiding short-radius elbows can therefore contribute to a reduction in energy loss.
**Reduce bends; avoid 'arches'**

The number of bends used can often be kept to a minimum by designing the system carefully. It is also always important to avoid having high points in pipelines where pockets of air could collect, which would be extremely difficult to get rid of. Any such 'arches' are unnecessarily disruptive, as any air pockets will interrupt the flow. This in turn will cause a complete loss of the siphon action and increase the pressure drop.

**Use free-flow valves**

Shut-off valves should be built into the system at various points to allow for the process to be stopped and started, and for specific parts of the system to be isolated for repairs or maintenance. By using valves of a type that fully retracts from the line of flow – as is the case with a gate valve – the pipe flow will not be obstructed, thus minimizing friction loss. However, if the valve remains in the line of flow – as is the case with a butterfly valve or a globe valve – then there will be some disruption to the flow, even when the valve is completely open, resulting in extra friction loss. The resistance coefficient is usually much lower with a gate valve than with a butterfly valve or a globe valve. The same holds true for other valve types too, such as non-return and foot valves. The resistance coefficient with a hinged valve will of course be much lower than with a full-lift valve.

A significant contribution to energy saving can therefore always be made by using those free-flow valves that have the lowest possible resistance coefficient ($k$ or $\zeta$).

**Minimize pressure loss throughout**

All in-line equipment, such as heat exchangers, filters and static mixers, will require a difference in pressure to overcome the friction losses. If there is a choice of products then this difference in pressure should be the deciding factor when making your selection. For instance, a plate heat exchanger that is more expensive than a pipe heat exchanger is definitely worth investing in if the price difference can be offset later against a reduction in energy losses.

**What savings does the difference make?**

Fluid velocity – the velocity of the fluid through a pipe – greatly affects friction loss, which can be reduced by keeping the velocity down. Within appropriate limits, a larger pipe diameter should be used for a given volume, as discussed above.

Take the example of a quantity of water that has to be piped 100 metres at 100 m$^3$/h. The pipe has five bends (with a standard radius of 1.5 × diameter) and one gate valve.

Using standard steel pipes a choice of different diameters can be made, as illustrated in Table 1. The energy loss is based on efficiency rates of 75% for the pump and approximately 90% for the drive. Energy costs are based on operating 24 hours a day, 365 days per year (8760 hours) at a presumed cost of €0.10 per kWh.

This table clearly shows that Europump’s recommendations lead to efficient energy use. It can easily be adapted to suit any individual situation.

**Conclusion**

Energy can be saved by finding ways to reduce friction loss at the design stage. It is of crucial importance to limit the velocity by choosing pipes with the correct diameter. It will frequently be necessary to choose more-expensive components with a lower
friction loss. However, the initial extra outlay can usually be quickly recouped as less energy will be used when the system is in operation. On top of that, the pump can be smaller and cheaper, since the required differential head is lower because of the reduced friction losses.

It is important to realize that the contractor building the system will not benefit from any savings that you, the user, are going to make from lower energy costs. Take care to avoid a situation in which the opposing interests of the two parties could lead to higher friction losses and greater energy consumption. Equally, false economies should be avoided with any investments.

References


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Table 1. Flow and energy loss data for standard commercial pipes*

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<tr>
<th>Nominal diameter</th>
<th>Velocity (m/s)</th>
<th>Friction loss (bar)</th>
<th>Energy loss (kW)</th>
<th>Energy costs (€/year)</th>
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*For the flow of water at a capacity of 100 m³/h.