Kelair Pumps Australia Pty Ltd ABN 28 001 308 381 215 Walters Road Arndell Park NSW 2148
Ph: 1300 789 466 Fax: 02 9678 9455 Email: kelair@kelairpumps.com.au www.kelairpumps.com.au
QLD Fax: 07 3808 8758 VIC Fax: 03 9569 7866 TAS Fax: 03 6331 9102 WA Fax: 08 9248 2255

PUMPS STEAM TURBINES BUILDING & FIRE WASTEWATER SERVICE

PUMP CLINIC 6

SPEED VARIATION WITH CENTRIFUGAL PUMPS

Affinity Laws

There are fundamental laws which can be used to predict changes in pump performance with variations in speed. It is important in pump applications to be able to develop performance curves corresponding to various speeds from standard performance curves. The mathematical relationships between flowrate, head, power and speed which enable this are known as the *Affinity Laws.*

For variation in speed with constant impeller diameter, the following laws apply:

a) Pump flow rate (Q) varies directly with the speed (N)
i.e. $Q_1/Q_2 = N_1/N_2$

b) Pump head (H) varies with the square of the speed (N)
i.e. $H_1/H_2 = (N_1/N_2)^2$

c) Power absorbed varies with the cube of the speed (N)
i.e. $P_1/P_2 = (N_1/N_2)^3$

In using the above formulae, it is assumed that efficiency remains constant. In practice, the efficiency if slightly less at lower speeds since friction and drag constitute a larger proportion of hydraulic power. It is important to note that these laws do not apply to NPSH.

Example:

If you have a pump performance at a speed of 1300rpm, what is the performance at 880rpm (refer to following performance curve Page 2).

The first step is to select 5 operating points on the 1300rpm performance and tabulate as shown below:

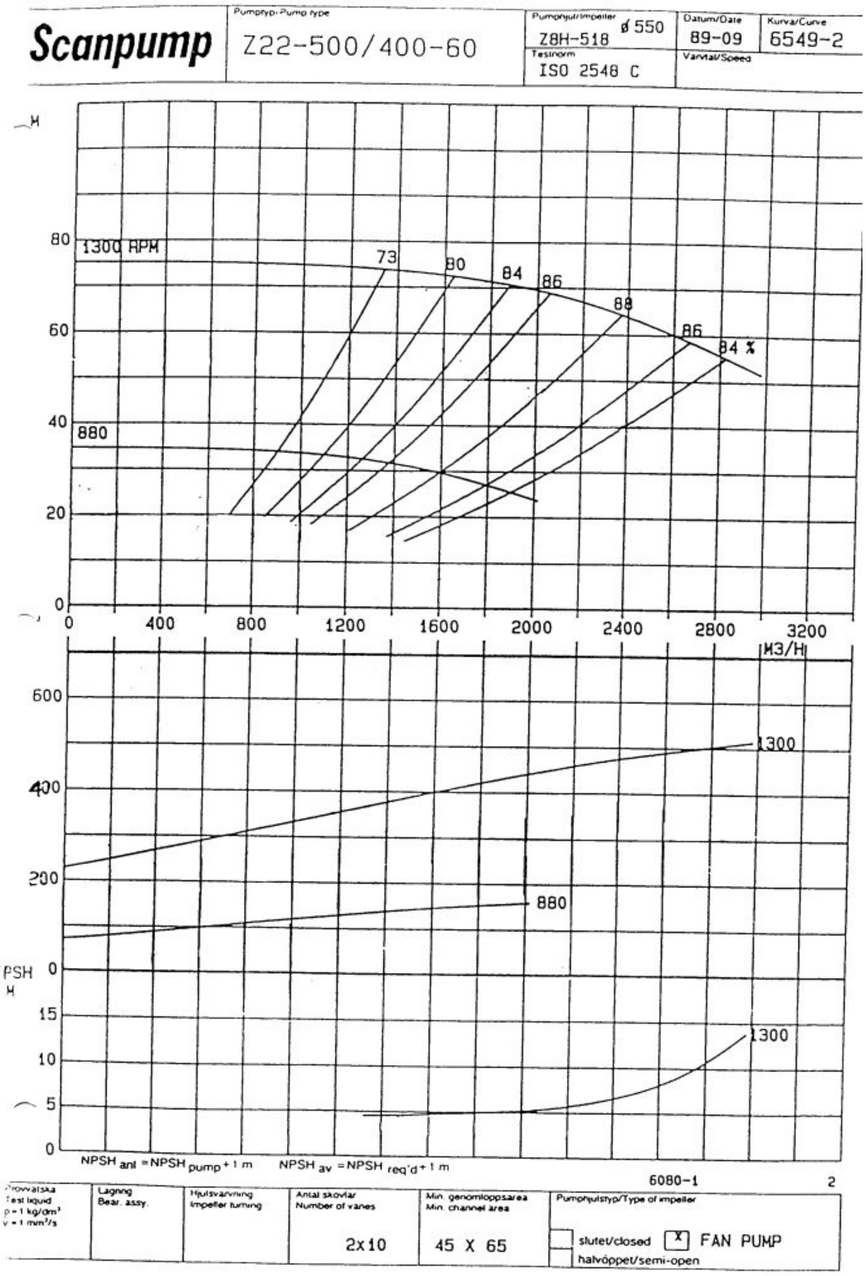
Flow (m^3/hr)	0	800	1500	2200	2800
Head (m)	75.5	75	73	67	56
Efficiency	-	-	77	87	84
kW *	230	313	386	460	507

* kW may be read from the power curve where efficiencies are not detailed or may be calculated using the formula.

$$\text{kW} = \frac{\text{Flow} \times \text{Head} \times \text{SG}}{k \times \text{Efficiency}}$$

Where: Flow is in l/sec or m^3/hr
Head is in metres
SG is specific gravity
Efficiency is to a decimal point i.e. 84% efficiency becomes 0.84

k = 102.2 if flow is in l/sec
= 368 if flow is in m^3/hr



Using the Affinity Laws, the following factors can be applied to the 1300 rpm performance figures when operating at 880 rpm:

Flow - (880/1300) i.e. 0.677
- $(880/1300)^2$ i.e. 0.458
- $(880/1300)^3$ i.e. 0.310

The new performance for the pump at 880 rpm is tabulated below:

Flow (m³/hr)	0	542	1015	1490	1896
Head (m)	34.6	34.4	33.4	30.7	25.7
Efficiency	-	-	77	87	84
kW	71.3	97	119.7	142.6	157

Pumps should be selected for maximum flow

The pump and the associated plant equipment such as pipes, valves and tanks must always be designed to cover for the maximum pumped volume. The following must be taken into consideration to determine the maximum capacity of the plant:

- Provision for increasing demand
- Excess demand for pumping capacity in exceptional circumstances, eg when the tanks are being emptied or refilled.
- In the event of emergencies, such as fire, heavy rainfall etc.

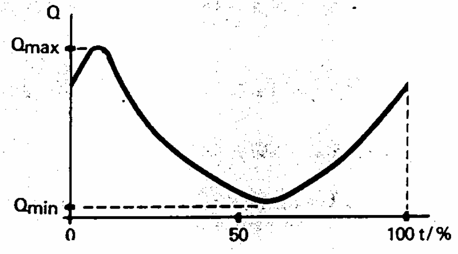


Fig. 1.1.
Variations in the pumped volume of liquid over different periods of time.

Q = Volume of liquid within a period of time
t = Time
Q_{max} = Max. flow
Q_{min} = Min. flow

Forms of Control

Since pumps are selected for the maximum plant capacity, a form of control must be provided to regulate the volume of flow for variation in pumping demands. An average pumped quantity Q_m may be only a fraction of the maximum pump capacity Q_p. The duration curve in Figure 1.2 below illustrates for example, how for the most part of over a one-year period, the pump may operate at reduced capacity.

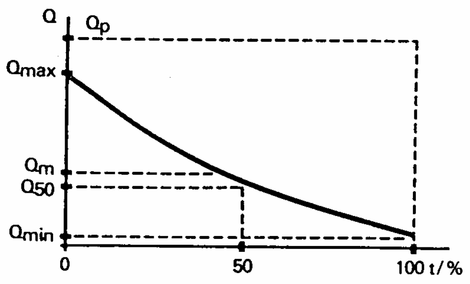


Fig. 1.2.
Curve in Fig. 1.1. converted into a duration curve.

Q_m = Medium flow

$$= \frac{1}{6} Q_{max} + \frac{2}{3} \cdot Q_{50} + \frac{1}{6} \cdot Q_{min}$$

Q_p = Max. capacity of the pump

Speed control is more economical than other forms of control

The pump flow can be controlled by using the following control methods:

- Throttle (or choke) control by means of a valve
- Start-Stop control of the pump
- Speed control eg, by means of a frequency converter

Throttle control is, even today, the most commonly used control form in industrial applications. Its efficiency is, however, very low when compared with speed control, which in many cases gives more than a 50% saving in energy. Pumps at waterworks and sewage water treatment plants are normally controlled by means of start-stop control. Its efficiency is often also poor (Figure 1.3) and besides, stress due to frequent starting and stopping may cause damage to the pipes and other plant equipment.

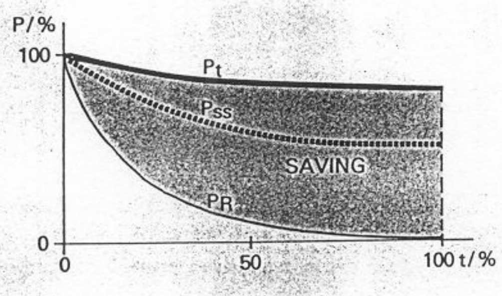


Fig. 1.3.
Approximate power requirements with various forms of control.

P_t = Choke control
P_{SS} = Start-stop control
P_R = Speed control

Energy Efficient

Throttle control means that the flow of liquid in the pipes is restricted by means of a valve. This results in a waste of energy because the pump is continuously working against the high pressure imposed by the valve. The power consumed by the pump can be calculated from the formula:

$$P = \frac{Q \times H \times \rho}{368 \times \eta}$$

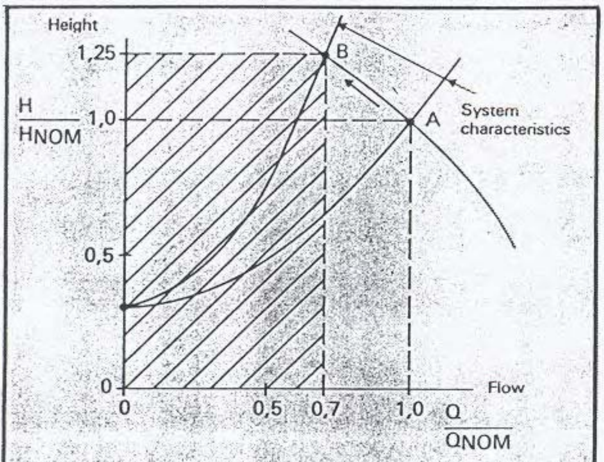
Where :

P = Power (kW)
Q = Pumped quantity (m³/hr)
H = Pump head (m)
ρ = Specific gravity of the liquid
η = Pump efficiency

The above formula shows that the power requirement P is directly dependent on the product of the pumped quantity Q and the pump head H. Figures 2.1 and 2.2 illustrate the power requirements which are represented by the hatched areas in both figures.

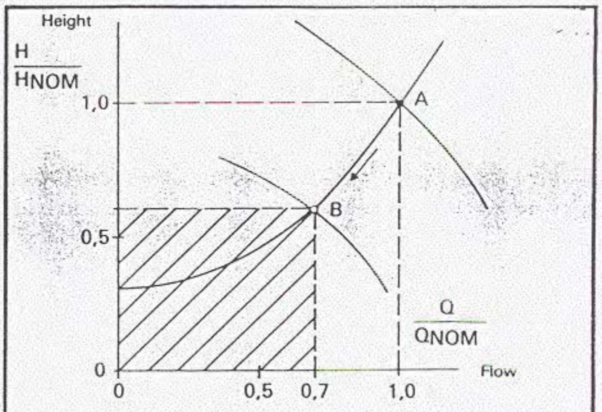
It can be seen that in this example, the power requirement with speed control is less than half of that with throttle control.

The saving obtained in energy depends essentially on the average pumped quantity. Figure 3 shows how much energy saving can be at different pumped volumes. When the power saving is known, the saving in energy can always be calculated by multiplying the power saving by the time factor. The methods of calculation are described in more detail (Page 1).



A = operating point with the maximum flow.
Power requirement = 1 x 1 = 1
B = operating point with a 70 per cent flow.
Q = 0.7 and H = 1.25
Power requirement ~ 0.7 x 1.25 = 0.875

Fig. 2.1.
Control of the flow Q of a centrifugal pump by means of a choke valve.



A = operating point with the maximum flow.
Power requirement = 1 x 1 = 1
B = operating point with a 70 per cent flow.
Q = 0.7 and H = 0.6
Power requirement ~ 0.7 x 0.6 = 0.42, i.e. less than half of the power requirement with choke control.

Fig. 2.2.
Control of the flow Q of a centrifugal pump by controlling the pump speed.

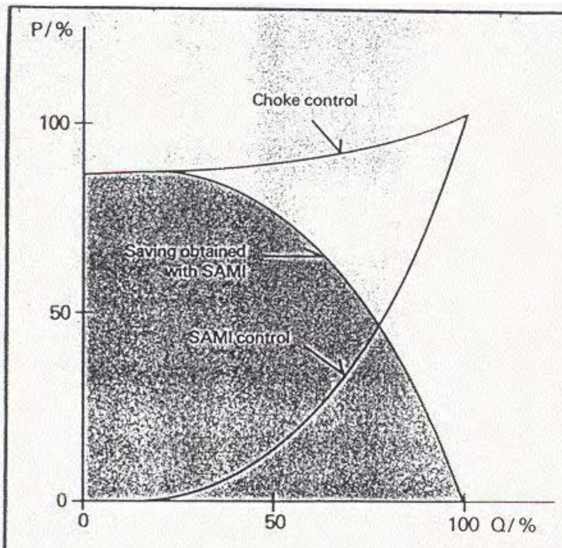


Fig. 3.
Dependence of the power saving on the pump flow Q.

Fewer pumps required

Control of flow is often arranged by means of two or more parallel-connected pumps which are of different sizes. Step by step control is thus achieved by running the pumps in turn. Improved control with a lesser capital cost is achieved if a single large pump is provided with the control as shown in Figure 4. Parallel-connected pumps and motors require additional valves and piping which again, increases costs.

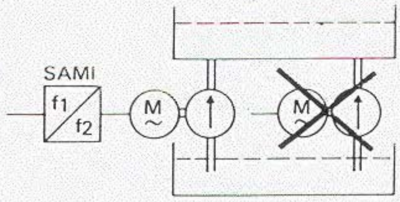


Fig. 4.
Parallel connected pumps of different sizes are not needed when speed control by means of a frequency converter is selected.

Reduced need for tanks

Pressure tanks and upper water tanks are used for keeping a uniform pressure in the pipes in applications where the pump runs on intermittent duty as, for example, in waterworks.

If the pump is provided with a frequency converter, the tanks can be made smaller or may be totally dispensed with. In addition to the lower investment costs, a better control result is achieved, which means a more uniform pressure at the consumer end.

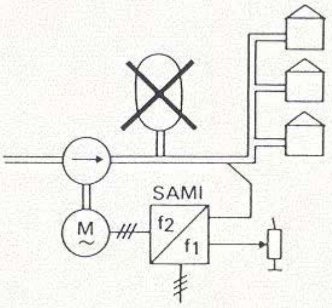


Fig. 5.
A pressure tank, for example, can be replaced by pressure control through a frequency converter.

Savings in electrical distribution costs

The starting current which a pump provided with a frequency converter takes from the electrical supply line is but a fraction of the starting current required by direct starting. On account of this, the electrical distribution equipment can be made smaller and be purchased at a lower price. A typical objective for saving purposes may be a standby generator for critical pumps. When a frequency converter is used for the speed control of the pump, the generator size need only be 30 to 50% of that previously required.

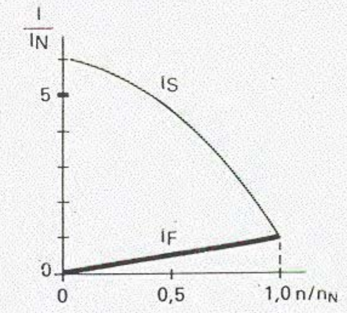


Fig. 6.
Line current on starting
I_N = Rated current of the motor
I_S = Current on direct-on-line starting
I_F = Current on starting by means of a frequency converter
n_N = Rated speed of the motor

Compensating capacitors can be dispensed with

Squirrel cage motors need reactive power which somehow needs to be generated. To avoid loading the distribution network unnecessarily with reactive power, compensation is normally effected by means of capacitors near to the motor. The frequency converter generates the reactive power required by the motor and no compensating capacitors are needed. The cost of investment is reduced and an optimum compensation effect achieved.

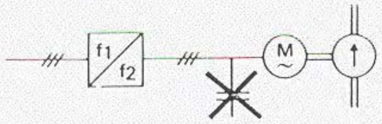


Fig. 7.
Control by means of a frequency converter improves the power factor of the drive and makes thus any compensating capacitors unnecessary.

Improved control effect

An improved control effect is more easily achieved with speed control than with other non-linear forms of control. A drawback of intermittent duty, for example, is the discontinuity of the control. The controlled parameters, the flow or pressure, for example, keeps varying. An accurate and linear control is achieved with the converter.

Figure 8 shows the control graph of a plant with three parallel-connected pumps P_1, P_2 and P_3. When one of the pumps (P_1) is provided with the control, a linear control curve (R) is obtained, whilst the curve (T) of intermittent control is stepped, which can lead to abrupt variations in the pumped volume of liquid.

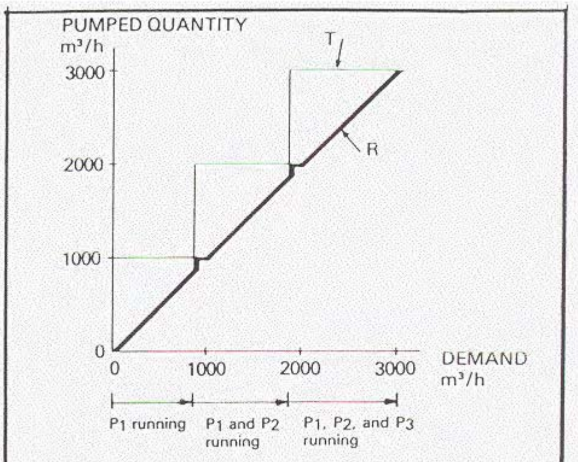


Fig. 8.
When one of three parallel running pumps (P1) is provided with the SAMI control, the achieved pumped quantity (curve R) is almost directly proportional to the demand, whereas a plant operating with intermittent control (curve T) produces great variations in the pumped volume of liquid.

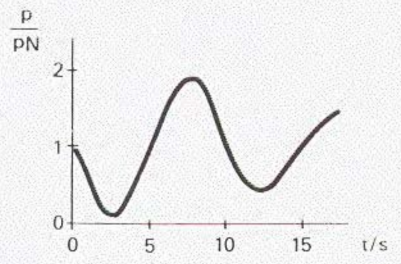


Fig. 9.
Pressure stroke in PVC plastic pipes which is due to the stopping of the pump.
PN = Rated service pressure
t = Time

Reduced maintenance costs

When the control is used, the pump, pipes and valves experience less wear, which means increased service life and reduced maintenance (particularly with plastic pipes).

- Static stress is reduced because the system need not operate with a high pumping pressure all the time as with choke control. The pressure is as high or low as required.

- Dynamic stresses are far lower with a smooth control than with an intermittent start-stop control. Pressure strokes (Figure 9) which wear the pipes and other plant equipment can thus be avoided, and the service life may even be doubled.

Calculate the savings yourself

1. Power requirement is determined:

(a) Either by means of the pump characteristics
The power requirement with choke control P_1 and with speed control P_2 can best be determined by means of the pump characteristic curves, provided that complete curves are available. P_1 and P_2 are determined according to Figure 10. When Q_M and the system characteristics are known, the pump curves η_1 and η_2 as well as the corresponding power curves P_1 and P_2 are found. The power requirements can be read at the point where Q_M and the power curves intersect.

(b) Or by means of calculation
If the complete power characteristics are not available, P_1 and P_2 are calculated from the following formulae. Choke control $P_{1:}$

$$P_1 = \frac{Q_M[m^3/h] \ \times \ H_1 [m] \times \rho}{368 \times \eta_1} \qquad \text{kW}$$

Speed control P2:

$$P_2 = \frac{Q_M[m^3/h] \ \times \ H_2 [m] \times \rho}{368 \times \eta_2} \qquad \text{kW}$$

2. Calculate the power saving
The power saving obtained by means of control is:

$$P_S = \frac{P_1 - P_2}{0.9}$$

Where the divisor 0.9 is the approximate efficiency of the motor.

3. Calculate the energy saving
The saving in energy per year is obtained when the power saving is multiplied by the operating hours, that is:

$$W_S = P_S \times t_a = \frac{P_1 - P_2}{0.9} \times t_a$$

4. Saving in money
The saving in money per year is obtained when the energy saving is multiplied by the unit price of energy k.

K_s [money saved per annum] = W_S [kWh/a] - k [price/kWh]

5. Cost pay-off time
The cost pay-off time is obtained by comparing the cost difference Kp between the speed control and the choke control with the achieved saving per year Ks.

$$t_t = \frac{\text{Kp [cost]}}{\text{Ks [money saved per annum]}}$$

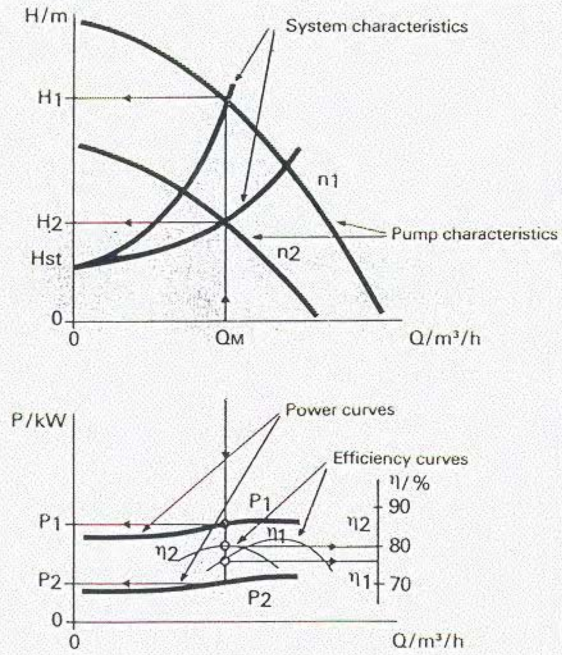


Fig. 10.
An example showing how the pump characteristics are used for calculating power requirements.

H_1 = Pump head at speed n_1
P_1 = Power requirement at speed n_1
η_1 = Efficiency at speed n_1
H_2 = Pump head at speed n_2
P_2 = Power requirement at speed n_2
η_2 = Efficiency at speed n_2

Example

The pump (as per following curve Page 11) is designed for a nominal duty of 2200m³/hr at 67.5 metres head. If a secondary flowrate of 1500m³/h is required for 50% of the time, what are the comparative power costs for throttling versus speed control.

By drawing system characteristics for the pump curves, we obtain:

$H_1 = 73\text{m}$ $\eta_1 = 0.765$ (throttling)
$H_2 = 31\text{m}$ $\eta_2 = 0.87$ (speed control to 880 rpm)

Power with throttling control:

$$P_1 = \frac{1500 \times 73 \times 1.0}{368 \times 0.765} = 389\text{kW}$$

Power with speed control:

$$P_2 = \frac{1500 \times 31 \times 1.0}{368 \times 0.87} = 145\text{kW}$$

Power saving:

$$P_S = \frac{389 - 145}{0.9} = 271\text{kW}$$

Energy Saving: (assuming 8000 hrs/annum total operating time)

$$W_S = 271\text{kW} \times 4000 \text{ hr/a} = 1084000 \text{ kW/a}$$

The saving in money and the cost pay-off time can be calculated by inserting the right values for the unit price of energy k and the capital cost difference K_p in the following formulae:

Saving in money: (based on power cost of 8¢ / kW hr)

$$K_S = 1084000 \text{ kW hr/a} \times 8¢ \text{ [cost/kW hr]}$$
$$= \$86720 \text{ per annum}$$

Cost pay-off time:

$$t_t = \frac{K_p \text{ [cost]}}{K_S \text{ [money saved per annum]}}$$