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Energy efficiency: benefits of variable speed control in pumps, fans and compressors

J. Schonek

Schneider Electric

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Foreword

no 214

Energy efficiency: benefits of variable speed control in pumps, fans and compressors

Jacques Schonek

**A graduate of the ENSEEIHT engineering school with a doctorate in engineering from the University of Toulouse, J. Schonek took part in the development of Telemecanique variable-speed drives from 1980 to 1995.
He was subsequently in charge of studies in the field of Harmonic Filtering and then Electrical Distribution architectures.
He is presently in charge of developing solutions for the «Water» segment of Schneider Electric.**

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Glossary

Energy efficiency:
Optimum use of electrical energy, including reduced consumption and cost and improved availability.

Variable speed drive (VSD):
A device used to control the speed of a machine.

Frequency converter:
A device used to adjust the frequency of the power supplied to a motor and thus control its speed.

Soft starter:
A device used to limit the inrush current when a motor is started and to control its acceleration.

Pump:
A device used to raise or move a fluid.

Centrifugal pump:
A pump in which the liquid is put into motion by a circular movement.

Fan:
A device used to displace air.

Compressor:
A device used to increase the pressure of a volume of gas.

Flow rate:
The quantity of a fluid conveyed per unit time.

Head:
The pressure at a given point in a circuit, expressed as the height of a column of liquid.

Useful power:
The power transferred to a fluid drawing a certain quantity of energy per unit time. Also referred to as the output power.

Mechanical power:
The mechanical power transferred to a machine (pump, fan, compressor) such that it can deliver a certain useful power to the fluid. Also referred to as the shaft power.

Electrical power:
Power drawn by the electric motor driving the machine. Also referred to as the input power.

Head loss:
Additional power that must be transferred to the fluid to overcome the various forces that oppose the flow.

Booster:
A device used to maintain a certain pressure in a fluid circuit, whatever the required flow rate.

Water hammer:
A sudden variation of the pressure in a circuit following an excessively fast drop in the flow rate due to the closing of a valve or the stopping of a pump.

Cavitation:
A phenomenon involving the formation and sudden collapse of vapour bubbles in a pump following a drop in the inlet pressure of the liquid.

Energy efficiency: benefits of variable speed control in pumps, fans and compressors

A large proportion of the electricity produced around the world is used to raise, move or pressurise liquids and gases with machines such as pumps, fans and compressors.

Given the increasing importance of controlling energy consumption, special attention must be paid to the way these machines are operated and the energy savings that can be achieved through variable speed control.

These different aspects will be dealt with in this Cahier Technique publication, both from the qualitative and quantitative standpoint. Variable speed drives are among the front-ranking solutions proposed by Schneider Electric to increase Energy efficiency.

Sommaire

1. Introduction

Electrical energy consumed by pumps, fans and compressors represents a significant proportion of the electricity used around the world. It is estimated that in industrial processes and building utilities, 72 % of electricity is consumed by motors, of which 63 % is used to drive fluid flow in pumps, fans and compressors.

Numerous industrial sectors have pumping, ventilation and compression needs. For example:

- In the Water sector, for lifting, irrigation, distribution, treatment, etc.
- In the Oil and Gas sector, for extraction, transport, refining, liquefaction, etc.
- In buildings, for heating, ventilation, air conditioning, etc.

Traditional methods of controlling flow rate or pressure involve varying the effective cross-section of the pipe or circuit through which the fluid flows.

Valves, taps and gates are the most commonly used devices.

However substantial energy savings can be obtained by using variable speed drives to control the flow rate or pressure in pumps, fans and compressors as opposed to the above physical or mechanical means. In pumping applications, the most significant savings are achieved with centrifugal pumps.

The aim of this document is to describe how centrifugal pumps, fans and compressors function in different operating modes, and to quantify the energy savings that speed control can generate. Other advantages of this technique in terms of Energy Efficiency are also reviewed.

2. Centrifugal pumps

2.1 General aspects

Centrifugal pumps cover a very wide spectrum in terms of power, flow rate and pressure. They are used in a host of applications, notably in the water sector. This is the most widespread type of pump.

The principle involves actuating an impeller that transfers mechanical energy to the fluid, which is then converted into potential energy (represented by the pressure) and kinetic energy (represented by the flow rate).

Figure 1 shows the main parts of a simple single-impeller centrifugal pump:

- the pump body, which comprises the inlet and outlet manifolds,
- the impeller, which is fixed to the drive shaft.

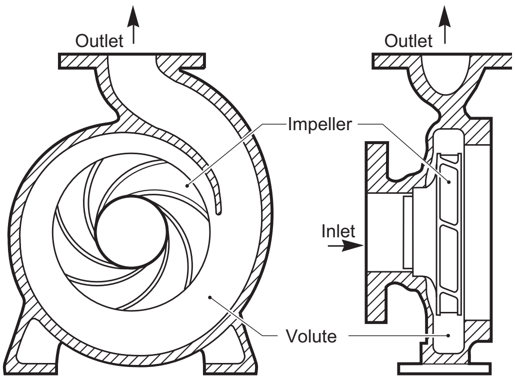


Fig.1. The main parts of a centrifugal pump.

Figure 2 shows a centrifugal pump driven by a three-phase asynchronous squirrel-cage motor, the most common type of electric motor used. These motors operate at a fixed speed when connected directly to the power grid, but are perfectly suited to operation at variable speeds when powered via a frequency converter.

Fig. 2. Centrifugal pump driven by an electric motor.

Different centrifugal pump configurations have been developed to cover a wide range of flow rates and pressures. In particular, the pressure can be increased by placing several pumps in series. **Figure 3** shows an example of a multi-stage pump.

Fig. 3. Multi-stage centrifugal pump.

2.2 Fundamental characteristics

A pump's fundamental role is to deliver a certain quantity of fluid in a given time at a given pressure. The major parameters used in pumping are therefore **flow rate** and **head**.

The flow rate (or discharge) Q represents the volume of fluid transported per unit of time and is expressed in m^3/s.

The head (H) represents the pressure at a given point of the circuit, expressed as the height of a fluid in a vertical column (in m).

Relationship between the head and the pressure: $Pr = \rho g H$

Pr: pressure (Pa)

ρ: density of the fluid (kg/m^3)

g: acceleration due to gravity ($9.81\ m/s^2$)

H: head (m)

In the case of water: $\rho = 1000\ kg/m^3$

A **pump's Total Dynamic Head** (TDH) represents the pressure differential the pump creates in the fluid between the inlet and the outlet, expressed as the fluid column height. The TDH varies according to the flow rate. The curve representing TDH as a function of flow rate is characteristic of each pump.

There is a different TDH curve for every pump drive speed.

The **Maximum Total Dynamic Head** (TDH_{max}) sometimes refered to as shut off head corresponds to the maximum pressure the pump can exert on the fluid, at a flow rate of zero. This corresponds to the maximum fluid column height the pump can maintain, as illustrated in **figure 4**.

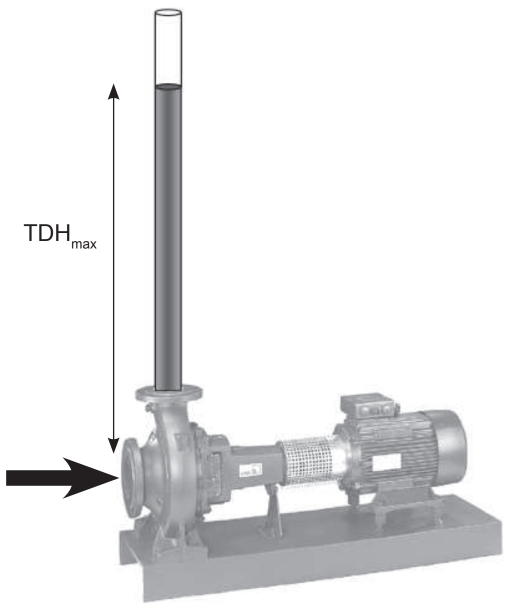


Fig. 4. Illustration: Maximum Total Dynamic Head.

The useful power (Pu) transferred to the fluid is given by the formula: $P_u = \rho gHQ$ (in W)
The **mechanical power** (P) supplied to the pump takes into account the pump's **efficiency** η, i.e.

$$P=(1/\eta)P_u=(1/\eta)\rho gHQ$$

The pump's **efficiency** η varies with the flow rate. It is zero when the TDH or flow rate are zero. This is the case because no power is transferred to the fluid.
The nominal operating point, or Best Efficiency Point (BEP), is defined as the point at which the pump's efficiency is at its maximum.

Figure 5 represents variations in TDH, efficiency and power as a function of flow rate, for a typical centrifugal pump

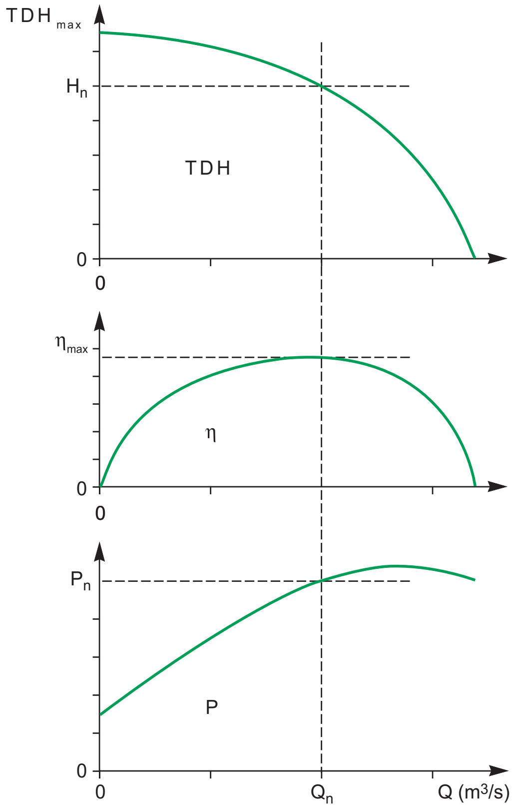


***Fig. 5.** Characteristic curves of a typical centrifugal pump.*

2.3 Operating point

The distribution circuit to which the pump is fitted is characterised by:
■ the water column height between the suction point and the point at which the fluid is used (total geometric height Z),
■ the head loss, corresponding to the additional pressure that needs to be exerted on the fluid to overcome friction in the conduits.
A simplified distribution circuit is represented in **figure 6**.

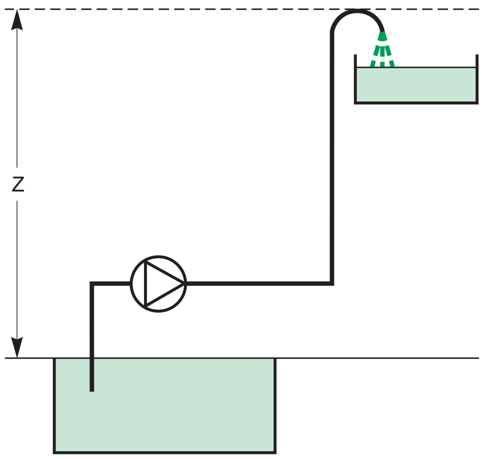


Fig. 6. Simplified distribution circuit.

The head loss R is proportional to the square of the flow rate. This results in a curve that is characteristic of the distribution circuit, as represented in **figure 7**.

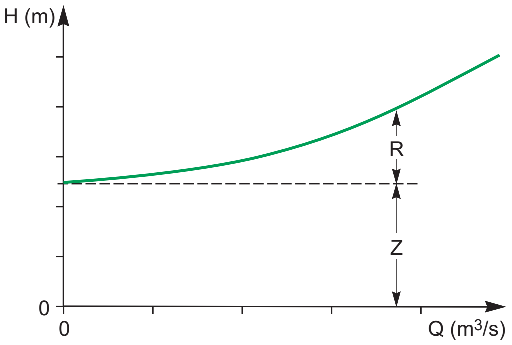


Fig. 7. Characteristic curve of a distribution circuit.

H: head at the pump
Z: water column height (static head)
R: head loss (dynamic head)

The operating point of the pump fitted to the circuit is determined by the intersection of the two curves characterising the pump and the circuit, as indicated in **figure 8**.
In this case, the useful power supplied by the pump to the fluid (equal to ρgHQ) is proportional to the shaded area.

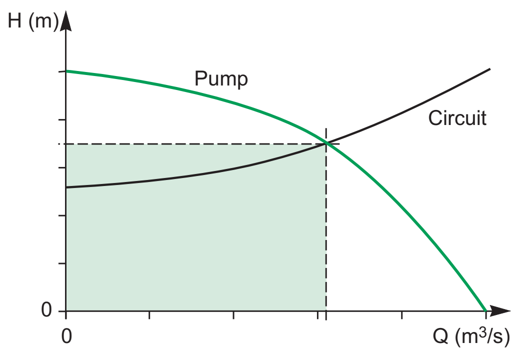


Fig. 8. Operating point of a pump in a circuit.

2.4 Varying the flow rate at a fixed speed

In most applications, the fluid flow rate to be supplied varies over time, according to the needs of users.

When using a fixed-speed pump, different methods can be applied.

Some of the most common solutions are outlined below.

Use of valves downstream from the pump

This aim here is to reduce the effective cross-section of the pipe downstream from the pump. This results in an increase in head loss in the circuit, which translates into an increase in the pressure at the pump outlet and dissipation of energy in the fluid.

In **figure 9**, point A is the operating point at the nominal flow rate Q_n. Point B is the operating point at the reduced flow rate Q_r. The circuit's optimal operating point at flow rate Q_r would be point C. The shaded area therefore represents the power lost with this type of operation.

Using a bypass circuit

The principle involves returning some of the pumped fluid back to the source, using a bypass valve. This allows the flow rate to be closely controlled but presents the drawback of low energy efficiency.

In **figure 10**, point A is the operating point relating to the nominal flow rate Q_n. The optimal operating point for this circuit at a reduced flow rate Q_r would be point C. The bypass valve located downstream from the pump makes practically no difference to its operating point. The shaded area therefore represents the power lost with this type of operation.

This type of operation allows a low flow rate to be achieved without running the risk of increasing the pump outlet pressure to an excessive degree.

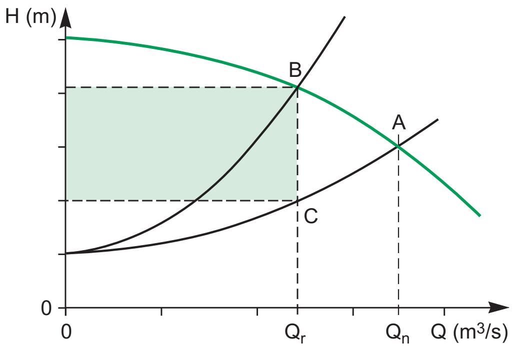


Fig. 9. Varying the flow rate using a downstream valve.

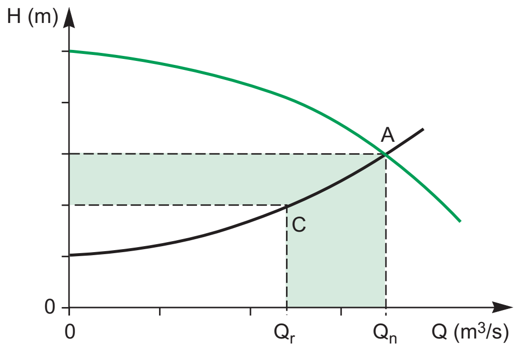


Fig. 10. Varying the flow rate using a bypass valve.

Intermittent operation

This operating configuration is commonly used to fill storage tanks such as water towers. The pump is selected so that it operates at an optimal level of efficiency for the water height in the circuit considered and the maximum flow rate required. The pump is switched on during the periods at which electricity is cheapest.

The drawback of this method is that operating the pump at its maximum flow rate means the head loss in the circuit is also at a maximum.

Parallel pumping

When the flow rate in a circuit needs to vary to a great degree, it is a good idea to place several pumps in parallel. This configuration, which is illustrated in **figure 11**, makes it possible to operate pumps as close as possible to their optimal level of efficiency.

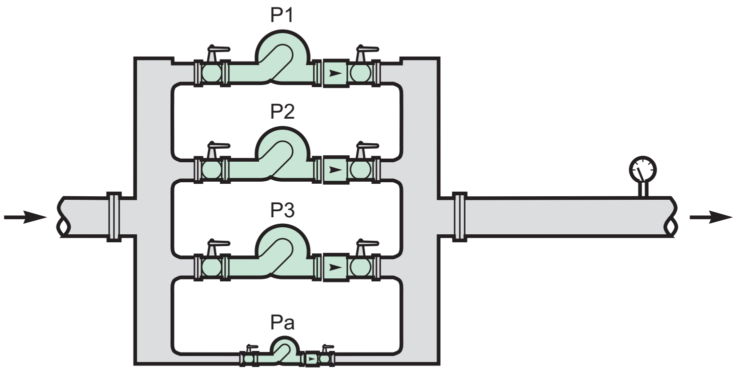


Fig. 11. Pumps in parallel.

If, for example, three identical pumps are installed in parallel, the resulting TDH curve is plotted point by point by adding together the corresponding flow rates at a given head.

In a given circuit, there are therefore three possible operating points, depending on the number of pumps in operation, as represented in **figure 12**.

Note that $Q_{1+2} < 2\,Q_1$.

This is due to the increase in system resistance (friction).

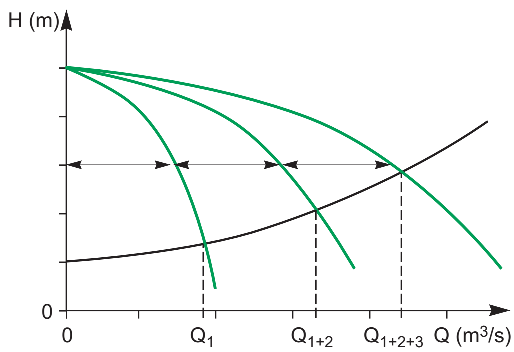


Fig. 12. Combination of identical pumps in parallel.

Intermediate operating points can be obtained by using a lower-powered auxiliary pump, as illustrated in **figure 13**.

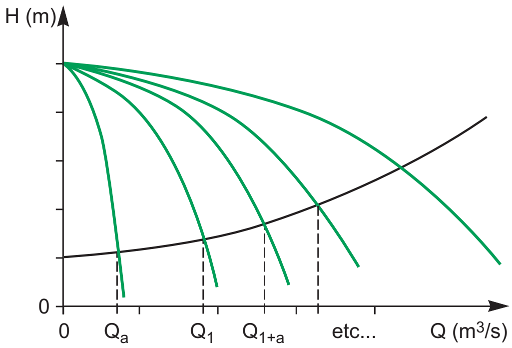


Fig. 13. Using an auxiliary pump.

Following the same principle, it is quite common for a low-powered "jockey pump" to be used to maintain the circuit at a minimum pressure when the main pumps are not in operation.

Note that parallel operation of pumps with different pumps curves may lead to stability problems and design of such a system should be verified by a hydraulics engineer.

Booster function

Pumps placed in parallel generally include a pressure regulation system, so as to maintain the pressure in the circuit between a minimum and maximum value.

An increase in demand results in a reduction in head losses, resulting from the opening of taps downstream, and a reduction in the pressure.

When the minimum pressure is attained, an additional pump must be put into operation. This operation is illustrated in **figure 14**.

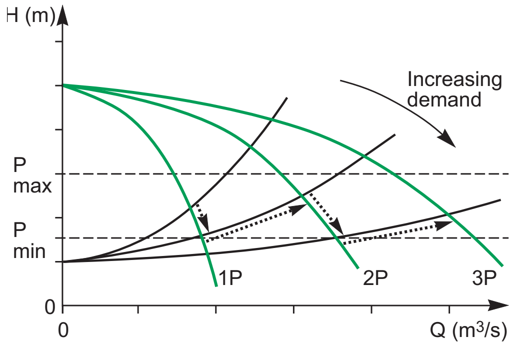


Fig. 14. Operation of a booster pump as the flow rate increases.

Conversely, falling demand translates into an increase in head losses, resulting from the closing of taps downstream, and an increase in the pressure.

When the maximum pressure is attained, a pump must be switched off. This operation is illustrated in **figure 15**.

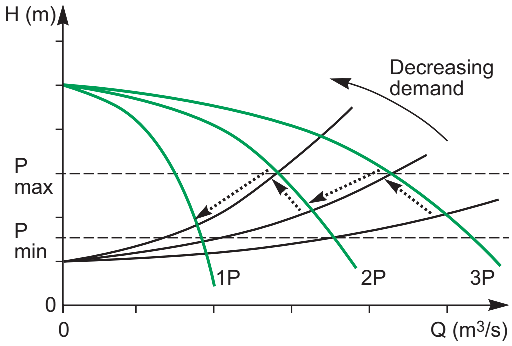


Fig. 15. Operation of a booster pump as the flow rate decreases.

2.5 Variable speed operation

The fundamental characteristics of a centrifugal pump are linked directly to its rotational speed. If we consider the pump on its own (without taking into account the water column height), at a rotational speed N other than the nominal speed N_n:

- the flow rate Q is proportional to (N/N_n),
- the total dynamic head TDH is proportional to $(N/N_n)^2$,
- the power P is proportional to $(N/N_n)^3$

Note that these pumps affinity laws are aproximation but are legitimate on a wide range of speed variation.

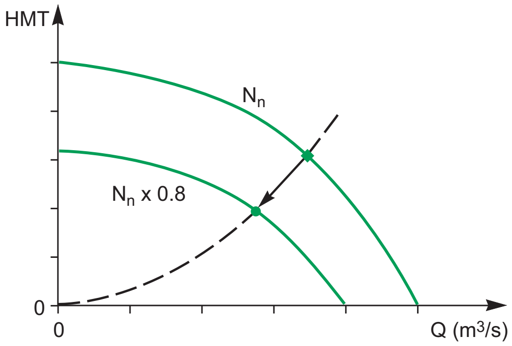


Fig. 16. Characteristic curves of a centrifugal pump at two different speeds .

Based on the characteristic curve at the nominal speed, the characteristic TDH(Q) curve at a different speed can be plotted point by point, with the homologous points being located on a parabola, as shown in **figure 16**.

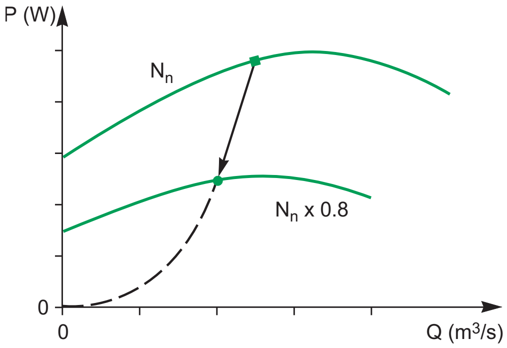


Fig. 17. Characteristic P(Q) curves of a centrifugal pump at two different speeds.

Similarly, the characteristic P(Q) curve can be plotted point by point, with the homologous points being located on a cubic curve, as shown in **figure 17**.

Varying the flow rate in a given circuit

We saw above that it is possible to vary the flow rate of a pump operating at a fixed speed using a valve placed downstream. This type of operation is illustrated in **figure 9**.

Figure 18 illustrates the power reduction achieved when the flow rate is varied by altering the pump's rotational speed. The useful power supplied by the pump is proportional to the shaded rectangular areas, therefore one can observe a significant reduction in power in the variable speed configuration.

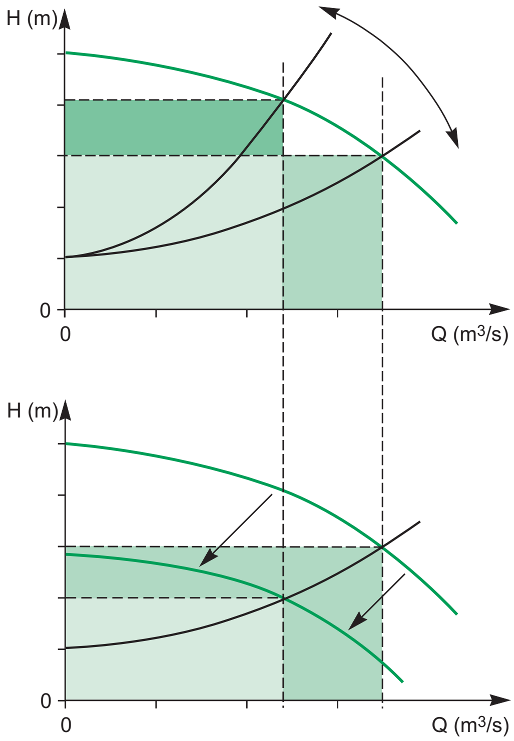


Fig. 18. Variation of the flow rate at a constant speed and with variable speed.

Varying the rotational speed makes it possible to use the pump at its highest level of efficiency at all times. In this case, the rectangular shaded areas are therefore directly proportional to the power drawn by the pump. In this example, the way the power drawn varies is illustrated in **figure 19**.

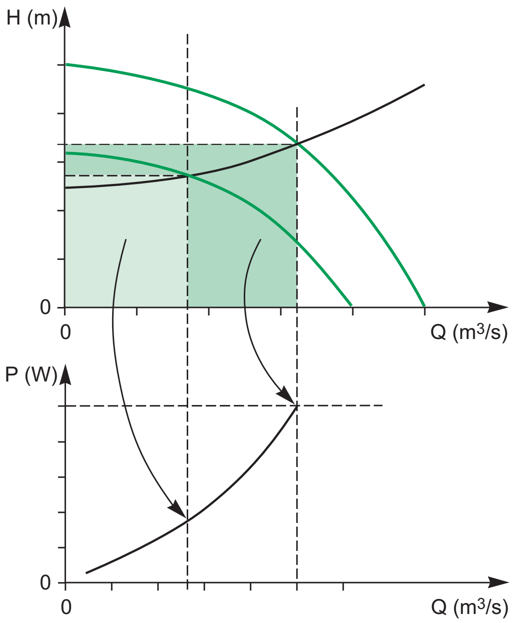


Fig. 19. *Variation of power with variable speed.*

Variation of power in different types of circuits

The variation in the power drawn by the pump as a function of the flow rate depends on the characteristics of the circuit to which it is fitted. The parameter to be taken into account is the ratio between the head at the pump's nominal operating point and the head Z at a flow rate of zero (see **figure 7**).

Taking H_n as the TDH at the pump's nominal operating point, one can define the following different types of circuits:

- Z = 0: circuit with head losses alone
- Z = 0.85 H_n: typical water supply (the geometric height is a preponderant factor)
- Z = 0.5 Hn: intermediate value

The top graph of **figure 20** shows that to obtain a similar reduction in the flow rate from Q_n to Q_r, the decrease in pump speed will be different depending on the type of circuit. This results in different curves for power as a function of flow rate, as shown in the bottom graph of the figure. The greater the decrease in speed, the greater the reduction in power.

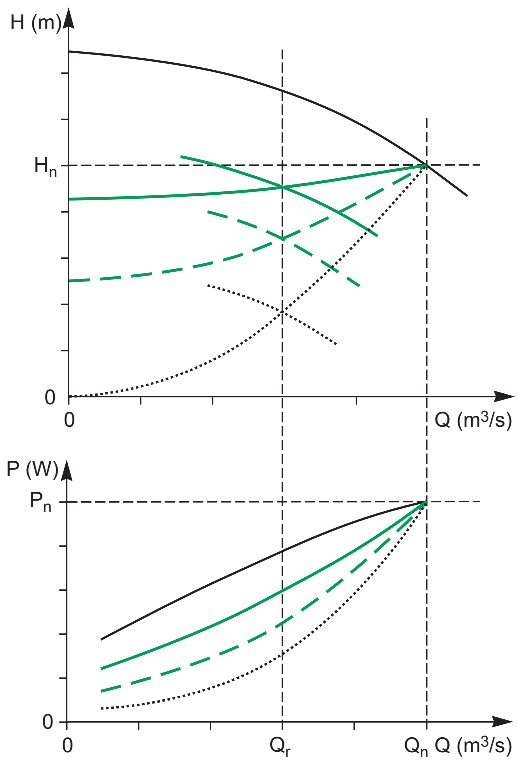
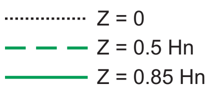


Fig. 20. *Variation of power for different types of circuits.*



Example of a power reduction calculation

Let us consider a motor-driven pump with an installed power of 100kW fitted to a circuit with head Z equal to half the pump's nominal TDH ($Z = 0.5 \cdot H_n$).

We wish to compare the energy consumed at 80% of the nominal flow rate when the pump is driven at its nominal speed with that consumed at a reduced speed. A valve is placed downstream to reduce the flow rate at the nominal speed.

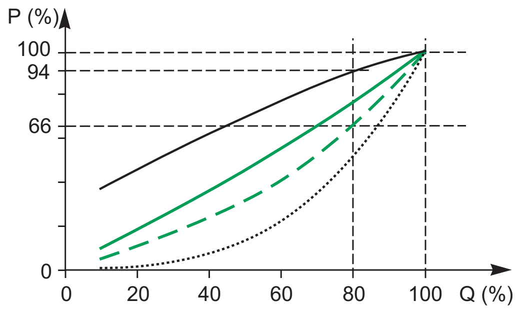


Fig. 21. Power variation.

Motor efficiency: η_{mot} = 0.95 at the nominal speed

η_{mot} = 0.93 at 80% of the nominal speed

Variable speed drive efficiency: η_{vsd} = 0.97

The power drawn in each case is presented by the curves above and specified in **figure 21**.

At a flow rate of 80 % of the nominal flow rate, the power drawn at the nominal speed is equal to 94 % of the nominal power.

At this same flow rate, the power drawn at reduced speed is equal to 66% of the nominal power.

Electrical power at the nominal speed:

$$P_f = P_n \cdot \frac{1}{\eta_{mot}} \cdot P(Q) = 100 \cdot \frac{1}{0.95} \cdot 0.94 = 98.9 \text{ kW}$$

Power at reduced speed:

$$P_r = P_n \cdot \frac{1}{\eta_{mot}} \cdot \frac{1}{\eta_{vsd}} \cdot P(Q) = 100 \cdot \frac{1}{0.93} \cdot \frac{1}{0.97} \cdot 0.66 = 73.1 \text{ kW}$$

The difference in power consumption is 25.8kW, which represents an energy saving of 226 MWh per year for continuous operation, and therefore a saving of € 11,300 per year, assuming a cost of € 0.05/kWh.

Eco*8* software

This Schneider Electric software application makes it possible, for general cases, to estimate the energy savings that can be achieved by varying the speed, as opposed to more traditional techniques such as throttling the flow by downstream valves or the use of bypass circuits.

Fig. 22. Eco8 software application.

Power reduction compared to intermittent operation

The intermittent use of a fixed-speed pump was discussed above as a possible solution for the adjustment of the average flow rate in a circuit. We will now provide an example of the savings that can be achieved by varying the speed.
Let us consider a circuit with head Z at a flow rate of zero is equal to half the pump's nominal TDH, i.e. $Z = 0.5\ H_n$
The head in the circuit as a function of flow rate is given by:

$$H = Z + k1 \,.\, Q^2 \qquad (1)$$

If Qn is the pump's nominal flow rate, we obtain:

$$H_n = Z + k1\ Q_n^2 \text{ with } Z = 0.5\ H_n$$

$$\text{then } k1 = \frac{0.5\ H_n}{Q_n^2} \qquad (2)$$

Substituing k1 in équation (1) leads to :

$$H = 0.5\ H_n \left(1 + \left(\frac{Q}{Q_n}\right)^2\right) \qquad (3)$$

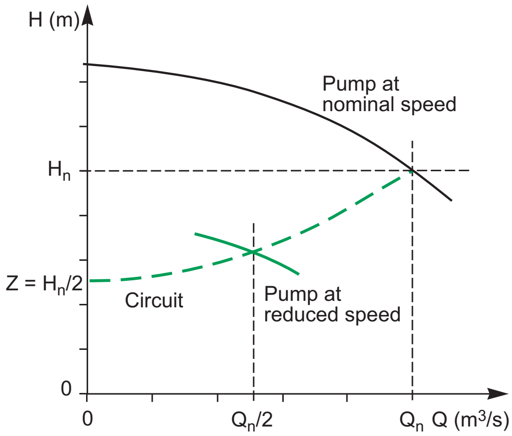


Fig. 23. Characteristic curves of the pump and the circuit.

Let the desired flow rate be equal to half the nominal flow rate. In the case of a fixed-speed pump, this requires intermittent operation at nominal power, with a duty cycle of ½.

The average power required will therefore be given by:

$$P_{avg} = k\ (½)\ H_n\ Q_n$$

The coefficient k takes into account the pump's efficiency, which is assumed to be optimal at the nominal operating point (H_n, Q_n).
When operating at reduced speed, the power will be given by:

$$P_r = k \,.\, H \,.\, Q_n/2$$

We can use the same coefficient k if we assume that the pump operates at reduced speed at its optimal level of efficiency.
The head H can be calculated using equation (3) with $Q = Q_n / 2$.
Thus, we obtain:

$$P_r = (5 / 8) \,.\, k \,.\, (½) \,.\, H_n \,.\, Q_n$$

Therefore: $\quad P_r = 0.62 \,.\, P_{avg}$

The use of a pump operating at reduced speed therefore allows the power drawn to be reduced by almost 40 % in this example, without taking into account energy losses in the motor and variable speed drive.

Variable speed parallel pumping

The operation of the multi-pump configuration presented above (see **figure 11**) can be significantly improved through variable speed.

The most commonly used configuration involves varying the speed of one pump and operating the others at a fixed speed. The use of a variable-speed pump allows the entire range to be covered (H,Q), as illustrated in **figure 24**.

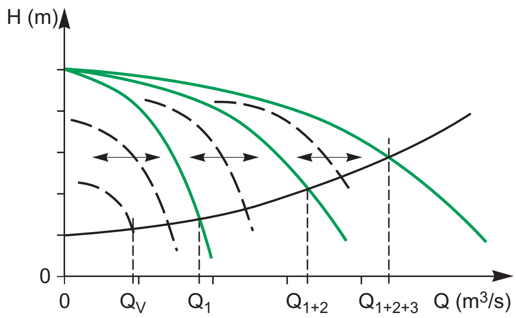


Fig. 24. *Using a variable-speed pump.*

The use of a variable-speed pump makes it possible to maintain the pressure in the circuit at a set value. If the pressure drops or rises compared to the set value, an acceleration or deceleration command is sent to the variable speed drive. If the pump's maximum or minimum speed are attained, one of the fixed-speed pumps is started or stopped depending on the case.

The variable-speed pump makes it possible to prevent large pressure differences, such as those represented in figures 14 and 15.

This system also allows a reduction in the number of motor starts and stops by preventing the large pressure or flow rate fluctuations that occur when a fixed-speed pump is started or stopped. This reduces stress on the motors and the risk of water hammer.

Comparison of different solutions

In the following example, different options are compared for flow reduction:

- Throttling
- One pump running at variable speed (lead pump) and other pumps running at fixed speed,
- All pumps running at variable speed

Let us consider a configuration with 3 identical motor-driven pumps in parallel, each one with a power at 100% flow equal to 100kW. The circuit static head Z is equal to half of the Total Head H_n of the circuit ($Z = 0.5\ H_n$).

A comparison of the different options is made at 70% of the total capacity, i.e. 210% of the nominal flow of one single pump.

The pumps characteristics are represented on **figure 25**, for different values of rotating speed.

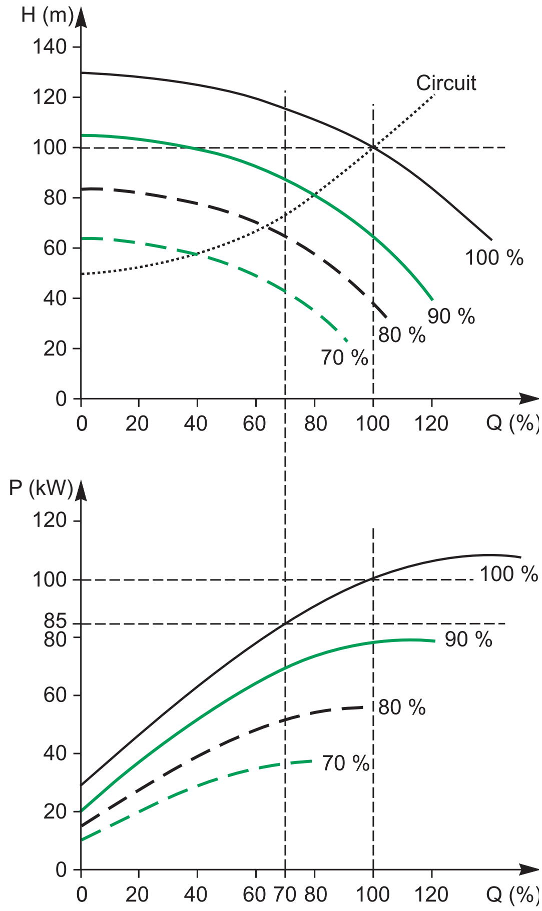


Fig. 25 : Pump and circuit characteristics.

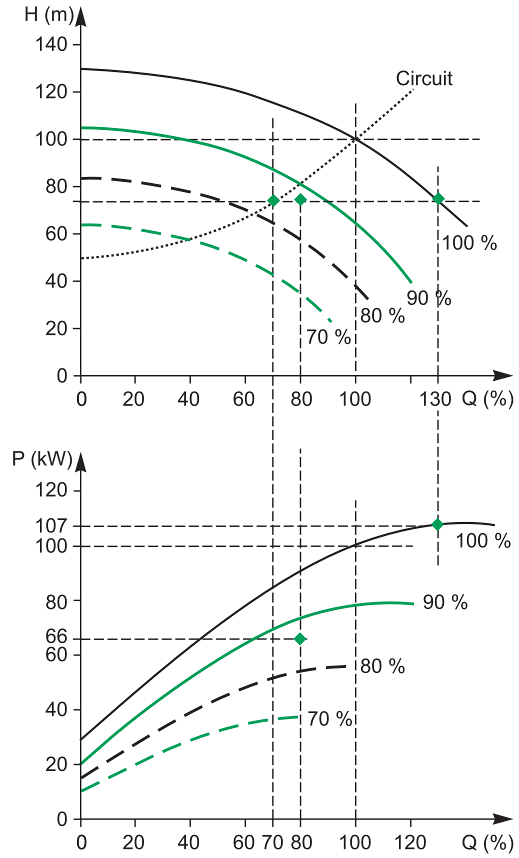


Fig. 26 : Using one variable-speed lead pump.

With throttling, the power of each pump running at full speed is reduced to 85 kW. The total power is then equal to 255 kW.

The operation with one lead pump at reduced speed is illustrated on **figure 26**. As a consequence, the flow of a pump running at full speed is increased to 130%, with an increase of the absorbed power (around 7%). As the requested total flow is 210% of the nominal flow of one single pump, only one pump running at full speed is necessary.

The flow delivered by the lead pump is then equal to 210 - 130 = 80% of the nominal flow. For this flow and head, the pump is running at approximately 87% of its nominal speed, and the absorbed power is around 66 kW.

For this option, the total power is then equal to 107 + 66 = 173 kW.

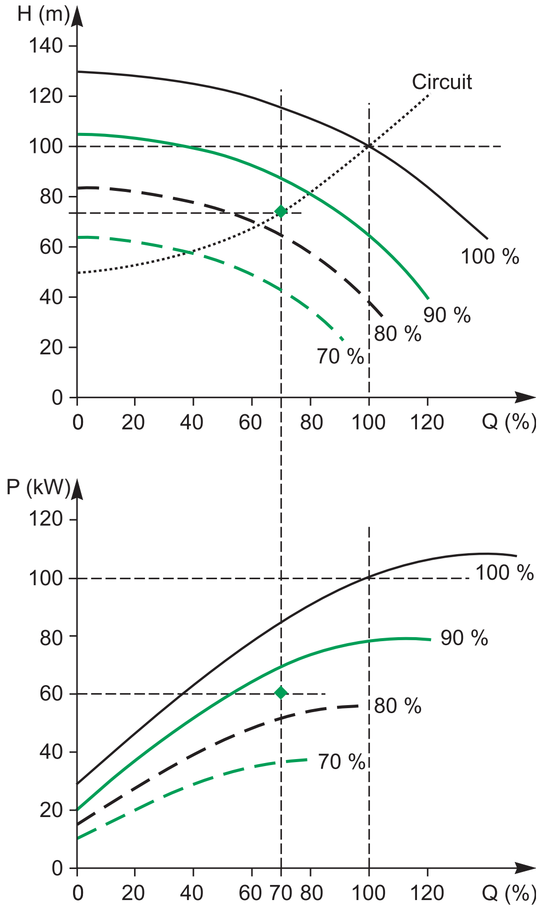


***Fig. 27 :** Using three variable-speed lead pumps.*

With all three pumps running at the same reduced speed, their speed must be adjusted to 85% of the nominal speed. The power of each pump is reduced to 60 kW.

The total power for this option is then equal to 3 x 60 = 180 kW.

It can be concluded that the use of variable speed brings a significant total power reduction. In the example presented here, the lead pump solution has the better efficiency, but the pump running at full speed must have a higher power rating.

Other advantages of variable speed

In addition to the advantages already mentioned, the use of variable speed enables greater flexibility in the design and running of installations. In particular it allows:

- The elimination of valves to adjust the maximum flow rate: if the pump is oversized, operation at reduced speed makes it possible to avoid the energy losses caused by a flow rate throttle valve.
- The reduction of noise and vibrations: the use of a variable speed drive means that the pump does not have to be used for extended periods at a fixed speed that may cause resonance in pipes.
- Less risk of water hammer and cavitation: these phenomena, which arise as a result of rapid variations in pump speed, are avoided thanks to the gradual acceleration and deceleration made possible by the variable speed drive,
- The replacement of two-speed motors and other obsolete speed control devices that offer low efficiency.
- Pump impeller life is related to impeller tip speed. As such reducing motor speed will improve impeller reliability
- Speed control allows the pump to operate at high efficiency. Operation away of BEP will reduce bearing and seal life.

Fig. 28. Schneider Electric's Altivar 61 range of variable speed drives.

To power such variable speed motors, Schneider Electric offers the Altivar 61 range of variable speed drives specially designed for pumping applications.

Additionnal pump control cards are available for even better control or for more complex applications.

3. Fans

3.1 General aspects

Fans are machines designed to propel a gaseous fluid with a low compression ratio. They are therefore governed by the same fluid mechanics laws that apply to centrifugal pumps, resulting in numerous analogies between the two types of machines.

There are many different fan configurations. **Figure 29** presents two examples of these: a centrifugal or radial fan, and a propeller or axial fan.

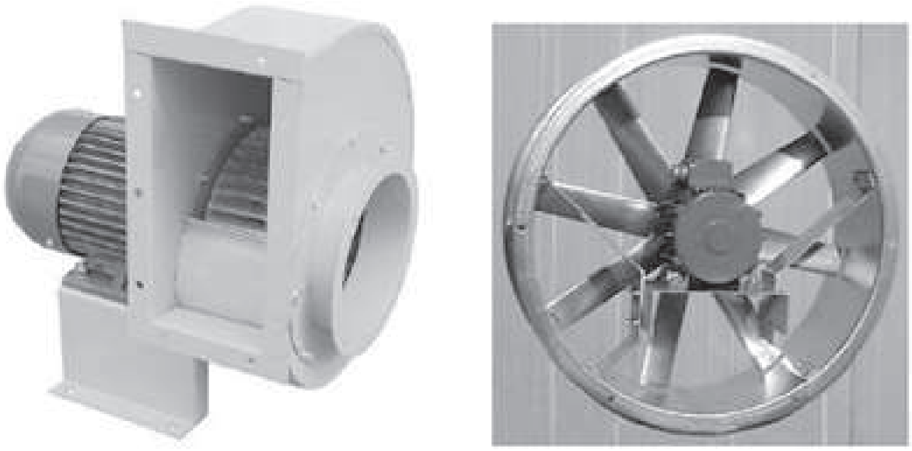


Fig. 29. Examples of a centrifugal fan (left) and a propeller fan (right) together with their drive motors.

The pressure differential created by the fan can be expressed in the form of a fluid's geometric height, as is the case for pumps. **Figure 30** shows the rate at which head H and power P, in the case of a centrifugal fan, vary as a function of the flow rate Q, at a constant rotational speed.

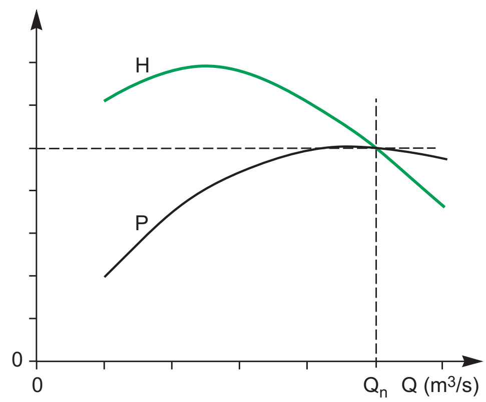


Fig. 30. Typical characteristic curves of a centrifugal fan.

In most cases, the outlet circuit exhibits no notable pressure differential (the circuit's inlet and outlet are both at atmospheric pressure). The shape of the circuit's characteristic curve can be explained by head losses that are proportional to the square of the flow rate. The circuit's H(Q) curve is therefore a parabola passing through the origin. The operating point of the fan fitted to the circuit is determined by the intersection of the two curves characterising the fan and the circuit, as indicated in **figure 31**.

The area to the left of the characteristic curve's peak must be avoided, as it presents the risk of instability, which would lead to flow rate and pressure oscillations, as well as abnormal noise and considerable mechanical stress.

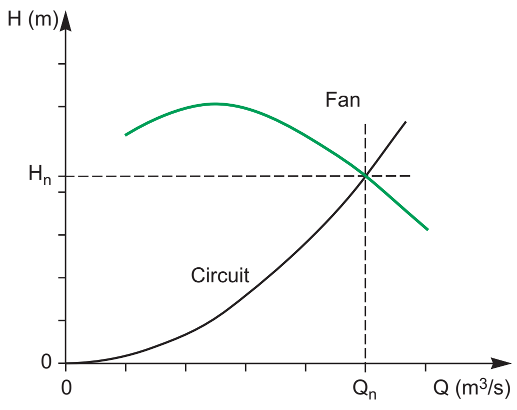


Fig. 31. Operating point of a fan in a circuit.

3.2 Fixed-speed operation

Different types of mechanical devices are used to vary the flow rate of fans operating at a fixed speed.

Devices placed downstream from the fan

The principle involves placing a device into the air conduit to control the circuit's head losses. Depending on the size of the conduit, the device can be either a valve or a single or multi-leaf damper.

This method is the simplest way of varying the flow rate, but its energy efficiency is low. This is illustrated in **figure 33**, which shows that the flow rate can be varied by modifying the circuit's characteristics. For the two operating points represented, the useful power values, which are proportional to the shaded rectangular areas, are very close. At low flow rates, a significant proportion of the energy is dissipated in the fluid.

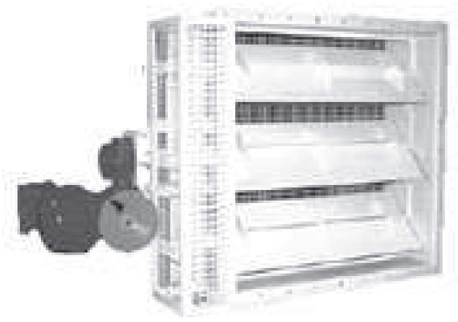


*Fig. 32. **Example** of a multi-leaf damper.*

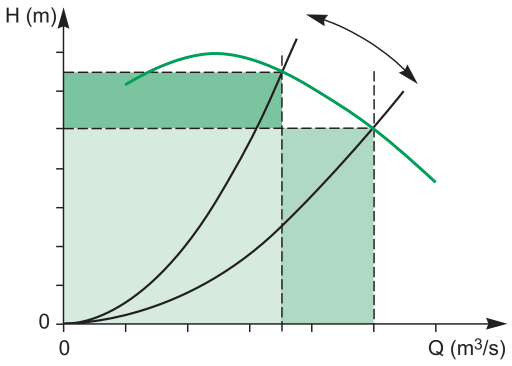


Fig. 33. Adjusting the flow rate with a device placed downstream .

Devices placed upstream from the fan

The aim of these devices is to alter the fan's characteristic curve, so as to displace the operating point while leaving the circuit's characteristic curve unchanged. Energy efficiency is significantly improved, because at a reduced flow rate the fan does not produce superfluous pressure.

Different technologies have been developed, including wicket gates, butterfly valves, dampers and guide vanes.

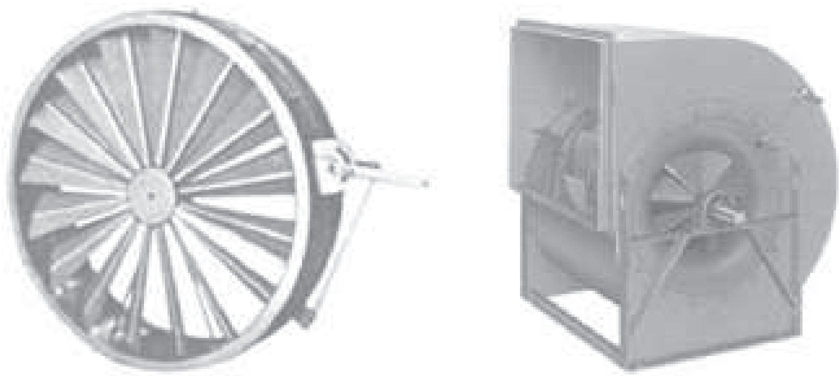


Fig. 34. *Examples of devices placed upstream: multi-leaf damper (left), guide vanes (right).*

With all these devices, the fan's characteristic curves are altered as indicated in **figure 35**. The useful power values are proportional to the shaded rectangular areas, and we can observe a significant reduction in power at a low flow rate. This alteration of the characteristic curves is accompanied by a smaller loss in efficiency than that caused by simply placing a damper at any point on the circuit.

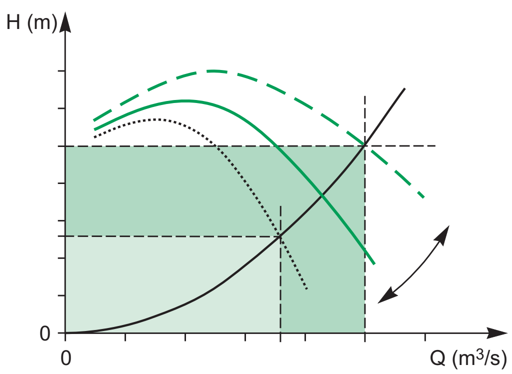


Fig. 35. *Adjusting the flow rate with a device placed upstream.*

Other devices

■ With propeller fans (axial), the flow rate can be adjusted by varying the angle of the vanes. Because of its mechanical complexity, this technique is only used for large fans. This method is highly energy efficient

■ The flow rate can also be adjusted using a bypass circuit, but this is uneconomical as energy consumption is constantly at a maximum, regardless of the effective flow rate.

Remarks:

In many cases, fans are oversized to obtain a maximum flow rate that is greater than the useful flow rate. Dampers are therefore installed to reduce the flow rate or the speed of the air at the outlet, and adjusted when the installation is put into operation. This results in constant head losses that reduce overall energy efficiency.

Another drawback of fixed-speed operation is that the noise level is always at a maximum.

3.3 Variable-speed operation

The fundamental characteristics of a fan are linked directly to its rotational speed. If we consider the fan in isolation, at a rotational speed N other than the nominal speed N_n:

- the flow rate Q is proportional to (N/N_n),
- the head H is proportional to $(N/N_n)^2$,
- the power P is proportional to $(N/N_n)^3$

Based on the characteristic curve at the nominal speed, the characteristic H(Q) curve at a different speed can be plotted point by point, with the homologous points being located on a parabola, as shown in **figure 36**.

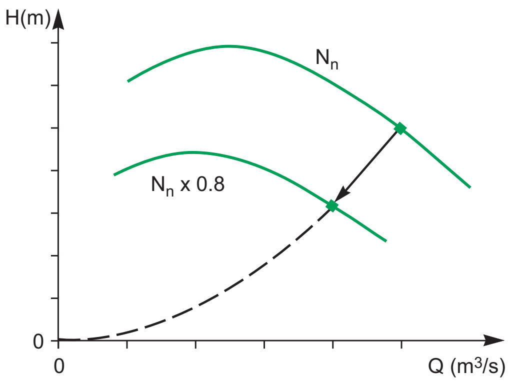


Fig. 36. Characteristic curves of a fan at two different speeds.

Similarly, the characteristic P(Q) curve can be plotted point by point, with the homologous points being located on a cubic curve, as shown in **figure 37**.

Figure 38 illustrates the shifting of the fan's characteristic curves at different rotational speeds and the resulting flow rate in a given circuit.

Varying the rotational speed makes it possible to always use the fan at its highest level of efficiency. This means that the shaded rectangular areas are directly proportional to the power drawn by the fans.

Speed variation is therefore the method that offers the greatest energy efficiency. **Figure 39** compares the variations in power resulting from the three main methods of varying the flow rate: device placed downstream, device placed upstream, variable speed.

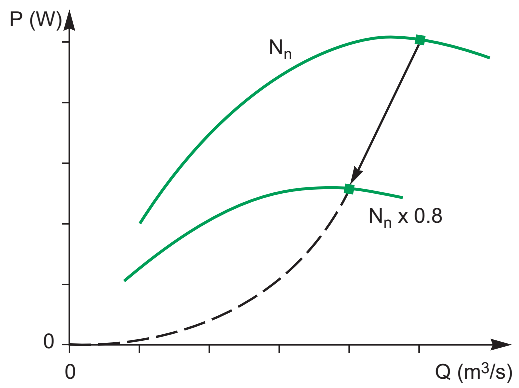


Fig. 37. Characteristic P(Q) curves of a fan at two different speeds.

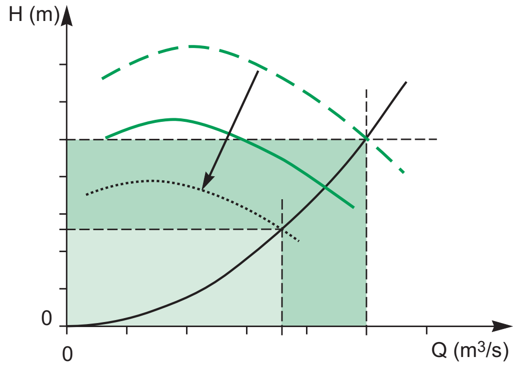


Fig. 38. Varying the flow rate by varying the speed of the fan.

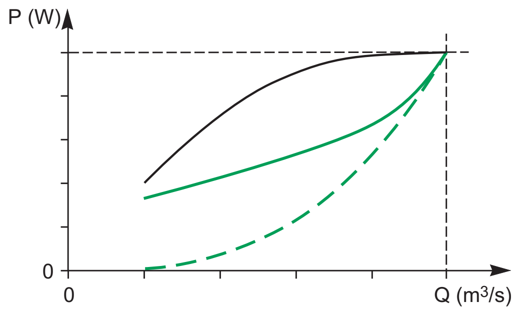


Fig. 39. Power versus flow rate for the different methods.

Downstream
Upstream
Var. speed

Examples of power reduction calculations

Let us consider a centrifugal fan with a nominal power of 100kW.

The fan is slightly oversized, which means that the maximum flow rate in the circuit must be adjusted to 90% of the fan's nominal flow rate to limit the speed of the air at the circuit's outlet.

In a 24-hour cycle, a flow rate of 90% is required over a 12-hour period (daytime), and a flow rate of 50% is required over the remaining 12-hour period (night time).

We wish to compare the different adjustment methods.

Motor efficiency:

- η_{mot} = 0.95 at the nominal speed
- η_{mot} = 0.94 at 90% of the nominal speed
- η_{mot} = 0.89 at 50% of the nominal speed

Variable speed drive (VSD) efficiency: $\eta_{vsd} = 0.97$

The power drawn by this fan using the different adjustment methods is illustrated by the curves shown previously in **figure 39** and detailed in **figure 40**.

The general power calculation formula at the nominal speed is as follows:

$$P_f = P_n \cdot \frac{1}{\eta_{mot}} \cdot P(Q)$$

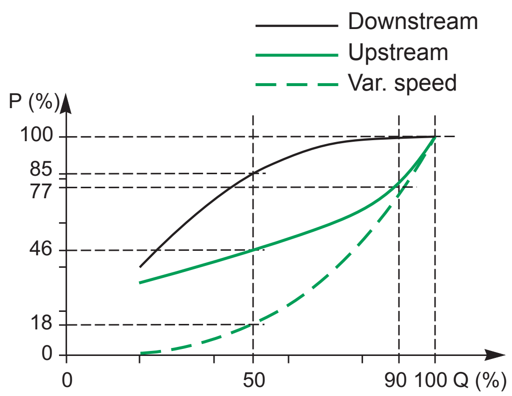


Fig. 40. Variation in power drawn.

At reduced speed, the formula takes into account the efficiency of the variable speed drive:

$$P_r = P_n \cdot \frac{1}{\eta_{mot}} \cdot \frac{1}{\eta_{vsd}} \cdot P(Q)$$

The table below shows the results of the power calculation for the different methods, in kW:

Setting:	kW at 0.9 x Q_n	kW at 0.5 x Q_n
Downstream	105	89
Upstream	80	48
Variable speed	84	21

The energy consumed is calculated by multiplying the power by the operating time, for each period (day and night): 12 hrs/day x 365 days = 4,380 hrs/year, assuming that the fan is running constantly.

Assuming a cost of €0.05/kWh, the use of variable speed allows annual savings of €19,600 compared with control using a device placed downstream, and €5,100 compared with control using a device placed upstream.

The Eco8 software application presented above allows this type of calculation to be performed for all cases (selection of the engine power, control of the upstream or downstream flow rate, definition of the operating speed).

Setting:	kWh
Downstream	852 947
Upstream	562 484
Variable speed	460 661

Fans operating in parallel

Gaseous fluids can be propelled at high flow rates by placing fans in parallel. Generally, identical fans are used. The resulting characteristic curve is obtained from the sum of the flow rates at equal pressure, as illustrated in **figure 41**.

We can see that in a given circuit, as a result of the quadratic increase in head loss as a function of flow rate, the resulting flow rate with two fans is not double the flow rate obtained with a single fan.

Flow rate Q_1 represented in **figure 41** can be obtained either by operating fan 1 alone at its nominal speed, or by operating both fans together at reduced speed. This type of operation is illustrated in **figure 42**, which represents the characteristic curve of both fans operating at the same time at the reduced speed N_r.

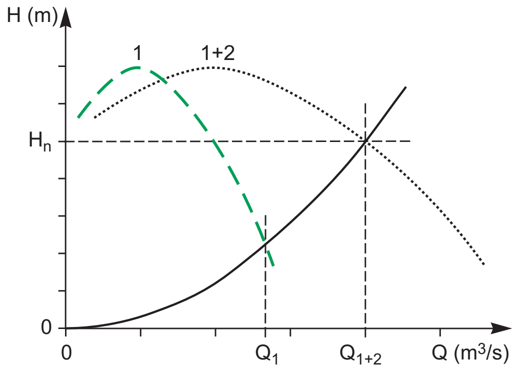


Fig. 41. Characteristic curve of two fans operating in parallel.

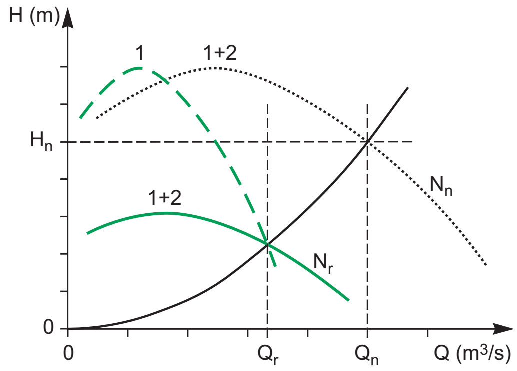


Fig. 42. Operation of two fans at reduced speed.

In the example represented, the reduced speed is equal to approximately 2/3 of the nominal speed N_n. Each fan therefore absorbs power equal to $(2/3)^3$ times the nominal power P_n of a fan.
The total power is therefore given by:

$$P_t = 2.\left(\frac{2}{3}\right)^3.P_n \approx 0.6.P_n$$

Operating two fans at reduced speed therefore brings about an energy saving of 40% compared with a single fan operating at the nominal speed.

The energy saving achieved is even greater with a multiple-fan configuration operating under a head that is very low or even zero.

For example, let us consider a configuration where six fans with nominal unit power P_n are placed in parallel, with no significant outlet pressure.

To obtain a flow rate equal to half the maximum flow rate, three fans can be operated at the nominal speed or all six fans can be operated at half the nominal speed.

In the first case, the power will be:

$$P_1 = 3.P_n$$

In the second case, the power will be:

$$P_2 = 6.\left(\frac{1}{2}\right)^3.P_n = \frac{3}{4}.P_n = \frac{P_1}{4}$$

Therefore, this is another example of energy consumption being substantially reduced when variable speed drives are used to adjust fans.

To control the speed of fans, Schneider Electric offers the Altivar 21 range of variable speed drives, which is particularly well suited to heating, ventilation and air conditioning (HVAC).

Fig. 43. *Schneider Electric's Altivar 21 range of variable speed drives.*

4. Compressors

4.1 General aspects

A compressor's fundamental role is to increase the pressure of a gas from the suction pressure to the discharge pressure.

Air and gas compression has numerous applications in industry. These include:

- The production of mechanical energy for different types of actuators (screw guns, pneumatic jacks, etc.),
- The production of industrial gases through liquefaction (nitrogen, oxygen, natural gas, etc.),
- Air conditioning and refrigeration,
- Aeration in wastewater treatment facilities.

Requirements in terms of flow rate and pressure vary greatly, which is why different technologies have been developed. The most common are:

- Centrifugal compressors,
- Screw compressors,
- Piston compressors,
- Vane compressors,
- Turbochargers.

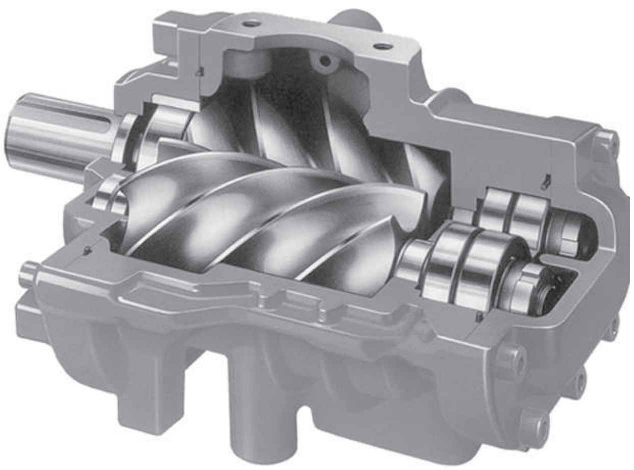


Fig. 44. *Example of a screw compressor.*

In general, the torque developed increases with the speed, but the starting torque can sometimes be high, as is the case with piston compressors.

As we saw above with pumps and fans, the compressor's operating point depends on the characteristics of the fluid circuit, as illustrated in the following figure (for a centrifugal compressor).

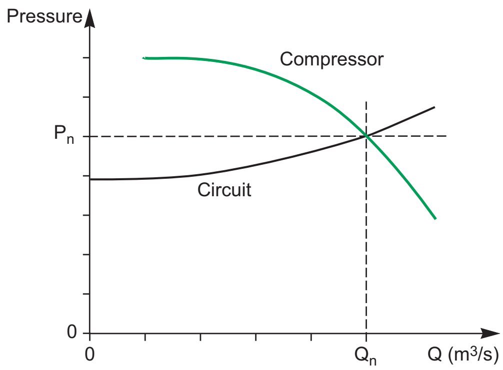


Fig. 45. *Operating point of a centrifugal compressor.*

4.2 Variable-pressure operation

To cater for fluctuations in system demand, all compressors are coupled with a pressure regulation device. The main adjustment methods, which are suited to the characteristics of different technologies, are recalled below:

- Starting and stopping the compressor. Intermittent operation is suited to low-power devices that can be started frequently with no unacceptable drawbacks. During phases of operation, the compressor operates at its optimum level of efficiency.
- Recirculating or evacuating excess flow. This operating method is only applicable to low-power systems, because of its low energy efficiency.
- Partial or total load shedding by shutting the compressor's suction flap or valve. The compressor operates at reduced or zero load, thus reducing the electrical power drawn.
- Placing several units in parallel. The number of compressors in operation can be adjusted on demand.
- Varying the compressor speed. This method is the most energy efficient.

4.3 Variable-speed operation

Varying a compressor's speed is a method well suited to most technologies. It presents a number of major advantages:

- Gradual start up: no current peaks, reduced mechanical stress,
- Precise pressure regulation: the compressor's speed and therefore flow rate can be adjusted on demand, which reduces the amplitude of pressure fluctuations and the size of the buffer tanks required,
- Optimum efficiency: operating without head losses in the circuit allows energy losses to be reduced.

Speed variation is also well suited to compressors operating in parallel. In general, only one of the compressors is driven at variable speed, while the others operate on an on-off basis.

The figure below shows typical power variation curves, when using different flow control methods.

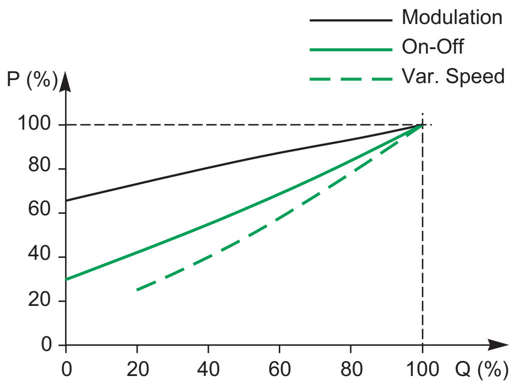


Fig. 44. Comparison of compressor control methods.

5. Conclusion

The use of variable speed in hydraulic machines such as pumps, fans and compressors is the key way of reducing energy consumption in numerous industrial and commercial installations.

The energy savings are particularly significant if reduced flow rates are used on a frequent basis. The sums invested in variable speed drives are paid back very quickly and subsequently generate considerable savings.

As well as energy savings, variable speed drives bring many other advantages to these applications. Thus, mechanical constraints, such as water hammer, cavitation and torque surges, are greatly reduced by the gradual and controlled acceleration and deceleration of the motor. The life expectancy of equipment is therefore extended. In addition, the management of the process is significantly improved and simplified, because it is possible to finely adjust the fluid flow rate and pressure.

An in-depth discussion of the operation of pumps, fans and compressors was beyond the scope of this document. Nevertheless, the key principles have been presented, together with examples that illustrate the extent of the energy savings that can be achieved through the use of variable speed drives.

Appendix 1: Bibliography

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Schneider Electric Industries SAS
89, boulevard Franklin Roosevelt
F - 92500 Rueil-Malmaison (France)
Tel : +33 (0)1 41 29 85 00

http://www.schneider-electric.com

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