Pump System Energy Efficiency Optimization Management and Technical Guide

The five most important points for the right system design:

- Design: design the system for effective and proper application conditions (water requirement, heat requirement)
- Losses: investment on minimum energy losses layout (short lines with large cross section, no unnecessary throttles and bends of the network)
- Variable operation: adjust amount of water and pressure under on-demand control
- Frequency converter: control the speed of the driving motor (instead of throttle or step switching)
- Efficient motor: high efficient motor adapted to pump for needs and speed

1. Pump basics

Pumps are turbomachines used to convey liquids (incompressible fluids). Pumps transform mechanical power provided by the motor to kinetic energy of the media (volume flow and pressure), aiming for:

- In the closed circle: to transport heat and pressure energy via the media. Examples: heating, air conditioning and cooling system.
- In the open circle: transport the material. Examples: water supply and sanitation and coolant.

Pumps are combined with their driving motor.
This brochure is intended for builders, planners and installers of building services, industrial and municipal enterprises and service companies. It mainly deals with medium and large centrifugal pumps of buildings and industries, where the motor is separated from the pumps. Small integrated pumps (so-called "wet runners"), large pumps over 1000 kW, diving pumps and various special applications (hydraulic pumps) are not targeted by this material.
The basic parameters of pump and system are:

- **The volume flow Q** is that the pump promotes usable volume flow through its outlet cross section (discharge nozzle) in a time unit (in m3/s, often in m3/h or l/s).
- **The delivery head H** defines the useful mechanical power transferred from the pump to the fluid. Energy delivered by 1 kg fluid is: $Y = gH_f$. The delivery head can be measured by the static pressures in suction and discharge nozzle and the geodetic height difference and determined by calculated velocities in suction and discharge ports at a defined Q.

$$gH_f = Y = g\,(z_d - z_s) + \frac{p_d - p_s}{\rho} + \frac{v^2_d + v^2_s}{2}$$

$$H = z_d - z_s + \frac{p_d - p_s}{\rho\, g} + \frac{v^2_d + v^2_s}{2\, g}$$

- **Hydraulic power (flow rate) P_h**: The system hydraulic power is the product of mass flow and pressure.

$$P_h = \dot{m}\,Y = \rho\, Q\, Y = \rho\, Q\, g\, H_f$$

Shaft power (mechanical power) P_w: The mechanical power, which is supplied from the shaft, is greater than the hydraulic power due to the mechanical and flow losses in the pump. The mechanical power is normally supplied by the electric motor:

$$P_{Welle} = \frac{P_h}{\eta} = M\omega = P_{el}\, \eta_{Motor}$$

The typology of the pumps: Radial pumps, semi-axial pumps (also called diagonal pumps) and axial pumps belong to the category of centrifugal pumps. Figure 3 shows the application areas of the individual pump types. The specific speed n_q characterizes the respective pump design.

2. Choice of pump system components

2.1 Selection criteria of pump

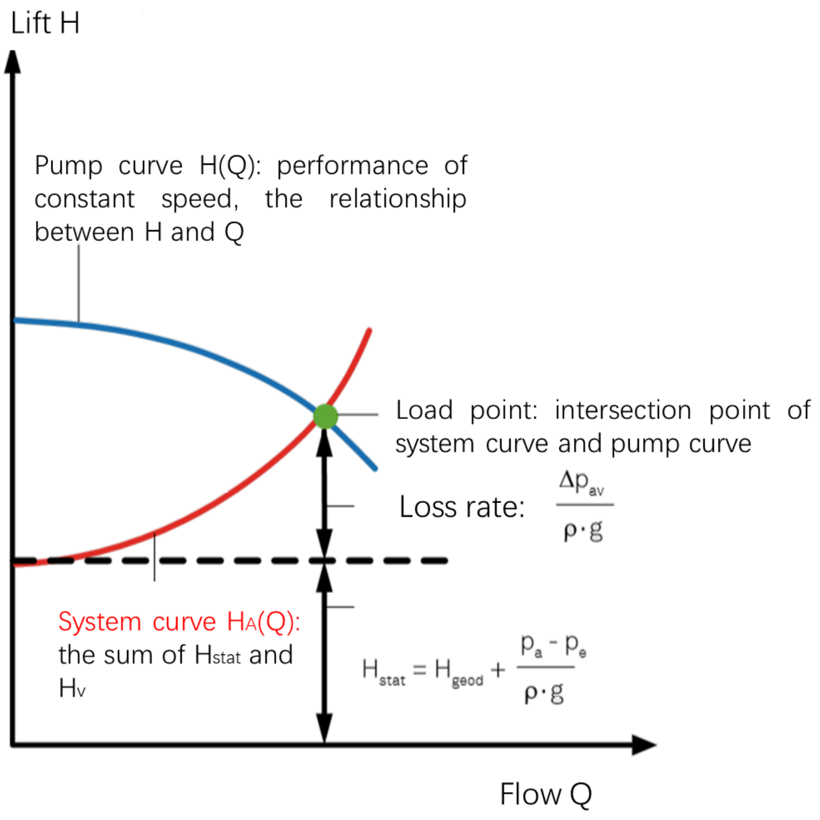
- **Operating data**
  - Flow volume, inlet pressure, outlet pressure, NPSH value of the system
- **Delivery fluid (media)**
  - Composition, if a mixture of media is present, density, viscosity and vapor pressure at defined working temperatures
  - Solids content, corrosive and erosive material
  - Undissolved gas components
  - Hazard potential, such as explosive, flammable, toxic, corrosive, etc.
  - Higher viscosity requires higher NPSH, reduces the hydraulic power and requires a larger driving power. The motor must be re-dimensioned if necessary.
- **working conditions**
  - Maximum and minimum media temperature
  - Ambient temperature and humidity
- **Material selection**
  - In addition to the strength properties of the fluid, the corrosion resistance of the fluid is to be affected by the pump. The corrosion resistance is influenced by temperature, concentration, content of impurities and abrasive solids as well through the maximum speed and flow control in the pump.

- **Pump dimensioning**
  - The capacity of the pump must be based on how the system is operated. It must be a pump with a suitable pump curve and appropriate motor.
  - The hydraulic power required in a system depends on the static heights to be overcome and pressure and the flow losses in the pipe lines. The system is characterized by its plant system characteristic.
  - Flow losses in the system are to be minimized to make economic sense in terms of system life and operating hours. Losses in the pump can be cut by choosing a pump with high efficiency.
  - The pump is optimally designed and energy-efficient if it does not exceed ± 20% (volume flow) away from its best point.

The ratio of flow volume Q [m3/s] and head H [m], the speed n [revolutions/min] and the physical properties of the pumped media determine the type of pump to be selected and the type of impeller. The characteristic parameter for the impeller type is the specific speed n_q:

$$n_q = n \frac{\sqrt{Q}}{H^{3/4}}$$

NPSH is an abbreviation of the Net Positive Suction Head and is a measure of the minimum allowable pressure in front of the pump to prevent cavitation damage. It is between holding pressure of the pump (NPSH required) and holding pressure level of the system (NPSH investment or NPSH present).



Plant system characteristic with static component

Example: Centrifugal pump

Before pump selection, the pump characteristic must be to be analyzed. It provides information about:

- Volume flow in relation to overcome height
- Efficiency and best point
- Shaft power (required input energy)
- Suction height requirements to avoid
- Steam bubbles (cavitation, NPSH required)
- Pump size and pump type
- Impeller size
- Rotating speed

Interpretation

- Operating point: intersection of network system curve and pump characteristic curve
- Design concerning: avoidance of cavitation damage with NPSHrequired

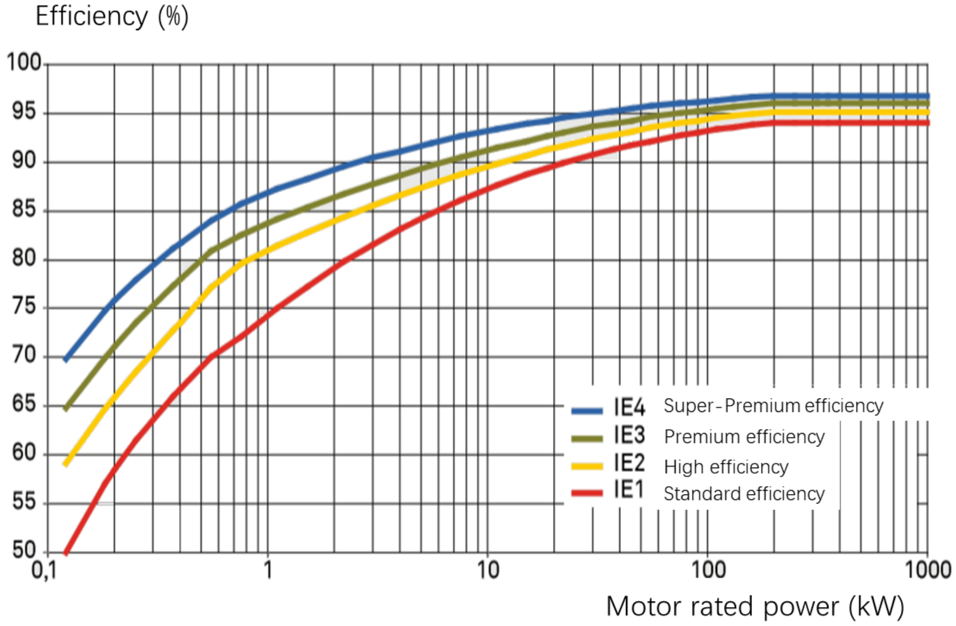
<NPSHsystem or directly off the quantities measured in s. Where: pv is the evaporation pressure (saturation pressure) of the water at the given temperature is and Hvs in the suction side. Height losses from system entry at e to the pump represent.

- Pump: $NPSH_{required}$ is provided by the pump manufacturer in product specification.

2.2 Selection of efficient driving motors

Depending on the required speed of the pump, motors with different numbers of poles can be used accordingly. Nominal synchronous speed (revolutions per minute): 2-pole with 3000 rpm; 4 pole with 1500 rpm; 6-pole with 1000 rpm; 8-Pole with 750 rpm.
The efficiency classes of the motor from 0.12 kW to 1000kW complies with IEC standard 60034-30. At low power levels up to 10 kW, the efficiency gains from IE4 to IE1 are very high in percentage terms. At larger powers from 100 kW to 1000 kW, although the percentage improvements are small, the reduction in losses in kW is very significant. The highest motor efficiencies can be achieved with electronically commutated permanent magnet or reluctance motors.
Attention: Motors of higher efficiency class (IE3 or higher) often have less slip than older, inefficient motors (IE1 / eff2). This results in a 1% Up to 5% higher rated speed. For the same impeller diameter this results in a 3% to 15% higher shaft power of the pump (the hydraulic power increases with speed changes with the 3 power!). This in an not intended effect results of high efficient motor replacement in closed systems, in which the desired efficiency gain will be lost again by an unnecessary increase in system output because of the increased flow is not needed. In open systems (material handling), the increased flow rate leads to shorter switch-on times, in which the increase of efficiency can therefore be realized. In individual cases, this leads to the fact that the dimensioning of the electrical motor must be checked.
Comparison speed and Power The pump power rises in the 3 times power with the number of revolutions.

Increase number of revolutions	Increase input and output power of pump
1%	3%
2%	6%
3%	9%
4%	12%
5%	16%



Efficiency of 4-pole electric motors of efficiency classes according to IEC 60034-30-1 (Draft revision 2012)

3. Energy-efficient pump system design for new plants

3.1 Tender of new equipment

It is important to adapt the pump characteristic to the system requirements. That means:

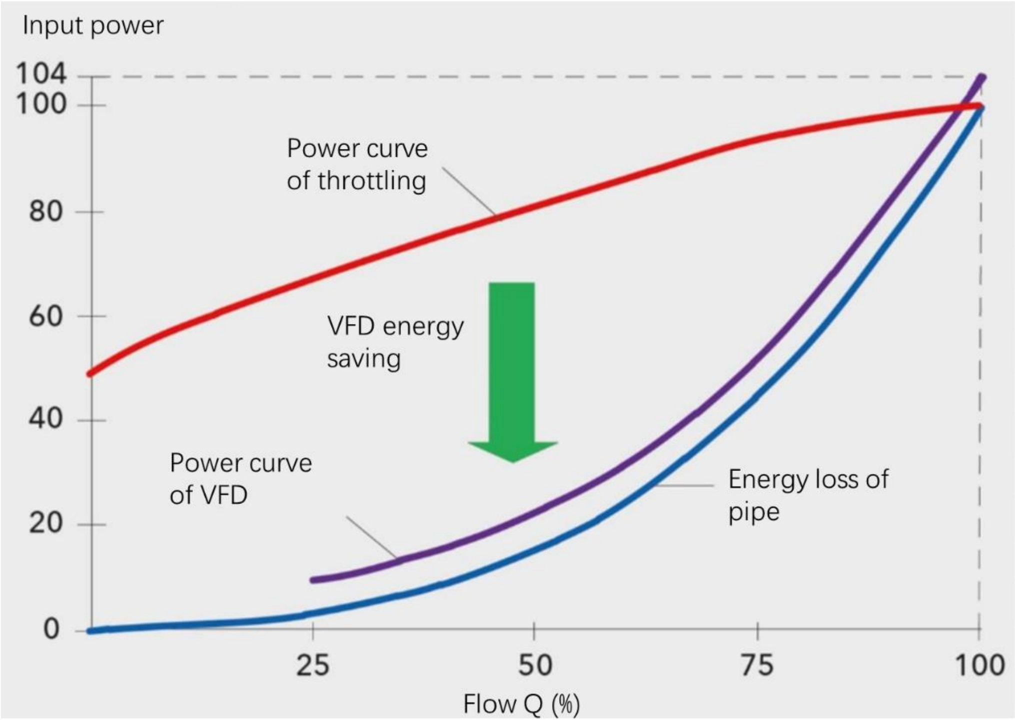
- Use in series or in parallel pumps
- Use smaller auxiliary pumps
- Adjust impeller diameter
- Use a drive with variable speed
- Replacing the existing motor with a new one with different speed (pole pairs)

If the use of the pumps deviates from their design, energy losses with non-energy-efficient control and increased costs are the result:

- Throttling control
- Bypass control

3.2 Load adaptation to demand

In many pumping systems, variable flows are required. It could be the process itself requires (e.g., temperature control) or that a reduced volume flow is sufficient (e.g. cooling). The saving potential through speed reduction is very large for closed circuits. The pump power (motor: torque and rotating speed; pump: volume flow and pressure) can be adapt by various measures.



potential savings media promotion in closed circuits

Adjustment pump performance

- Sequential connection of several pumps in series or parallel
- Adjust the impeller diameter of the pump (turn off)
- Throttles (energetically unfavorable)
- Bypass (energetically unfavorable)
- Transmission (pulleys, rare in pumps)
- Blade adjustment (only very large pumps)

Adjustment of the speed of electric motors

- Speed control by frequency converter (asynchronous, synchronous or permanent magnet motor)
- Voltage reduction (asynchronous motor)
- Speed levels due to other pole pair number or pole changeover

Speed control is not always useful. There are applications at where a speed control does not make sense; the unreflective use can also result in waste of energy and mis-investments. A typical example of this are lifting pumps in sewage treatment plants or water supplies, which usually multiple pumps are installed in parallel have storage tank, so no fine adjustment requirement of the low volume flow is needed. Here, the modest gain in efficiency from the pressure loss reduction with a smaller delivery volume is generally exceeded by the loss of efficiency in the pump and motor as well as by the internal consumption of the frequency converter.

For closed circuits, the characteristic pressure/flow rate conditions shows in Figure 6. The flow is practically proportional to the speed of the pump, the required delivery pressure differential (delivery head) is square and as a result, the required changes delivery power (corresponds

to volume flow times delivery head) with the cubic of the volume flow.
Example: a reduction of the volume flow by 20% results in a reduction of the pressure by approx. 36% (1 - 0.8*0.8), the pump energy is reduced by approx. 49% (1 - 0.8*0.8*0.8). For many processes, over 20% reduced volume flow during a large share of operating time is possible. Taking space heaters for example, a 20% reduced volume flow is hardly noticeable in the heat release.

Load control with frequency converter

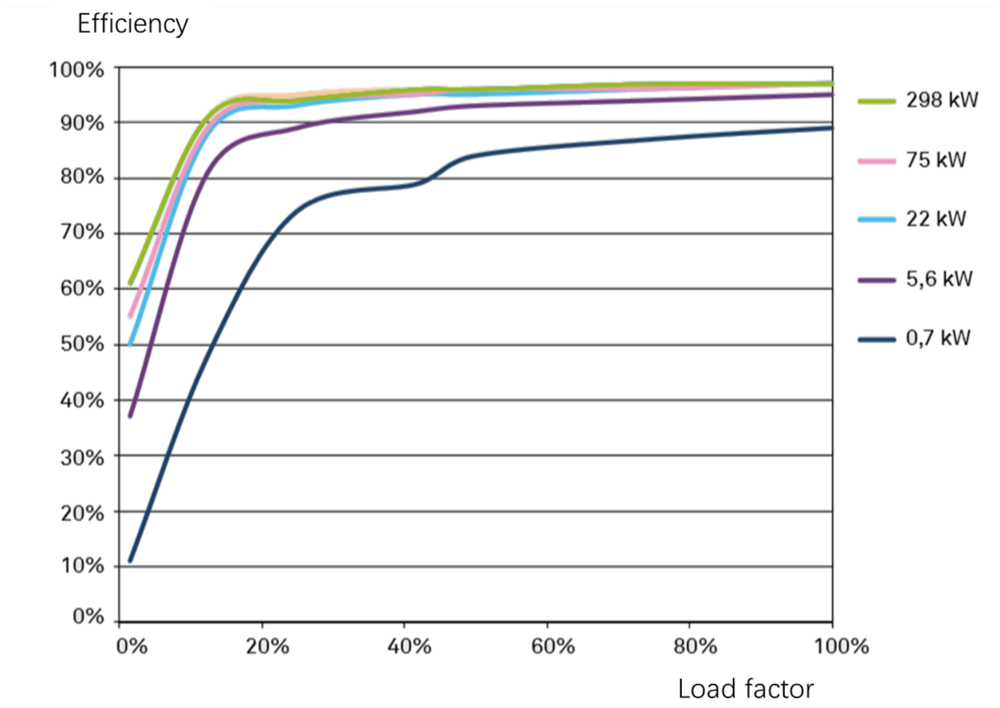
A frequency converter converts mains grid electricity with a frequency of 50 Hz three-phase current (at low power also 1-phase) electronically in a three-phase variable frequency current. This can be one of application adapted variable ratio of voltage and frequency are programmed. For media promotion in closed circuits, the tension (decisive for the magnetization) disproportionately reduced with decreasing speed, because the load of a turbomachine with the 3 times power of the speed decreases (Figure 6).
Because the output power of frequency converters is not quite sinusoidal (even with filters), the remaining harmonics cause additional losses in the motor. These must also be taken into account in a reasonable calculation.

Disadvantages of frequency converters

The frequency conversion is not free (Figure 7):

- An converter costs about almost as much as the same size motor.
- Efficiency of converter at rated load is 95% to 98%.
- At partial load below 20%, depending on motor or converter size, the converter efficiency decreases between 20% and 70%.

Motor cooling: At low speeds, the internal cooling of the motor (fan) may be insufficient because the harmonics losses in the winding still are quite high. A motor with converter operated at a speed of less than 50% for a longer period, needs a speed independent cooling (e.g. forced cooling fan or water cooling).
If actually variable power and speed takes a significant share of the operating time, motor operation with converter will make sense. If converter is only needed for start-up, other solutions may be cost-effective.



Efficiency of frequency converters
(Source: DOE EERE / CUB)

Particular attention should be paid when using speed control

Electromagnetic fields (EMF): VFD always cause relatively strong EMF. To avoid disturb others (electronic) devices and comply with the regulations, appropriate filters or shielding are required. The closer motor and VFD assembled, the easier the EMF to dominate, which is why VFD are frequently assembled instead of being installed in control cabinets. Regarding shielding and filters, the guidelines for installation from VFD manufacturers need to be considered. For larger motors (>50kW), due to eddy currents caused by the high frequency harmonics of the frequency converter, it might lead to bearing damage. Insulated bearings or sinus filters are recommended as the preventive measures.

Voltage reduction

Providers of electronic motor control units occasionally try to take the enormous savings potential from voltage reduction. If smaller torque is needed, voltage reduction is allowed in those devices and cases to save energy by reduction of magnetization, but the electrical speed is not reduced, which excludes the savings according to figure 6. A classic application for voltage regulation is for oversized motor, which always runs at partial load. Through voltage reduction to reduce magnetization, this is an efficient operation to be achieved. However, if the oversized motor is replaced with new efficient one, a proper re-dimensioned IE3 motor is a more economical choice. Since more than 90% of the lifecycle costs of a motor are electricity costs, the extra investment in higher efficient motor makes more sense than in in-efficient motor.

There are other useful applications for voltage regulators, especially for motor soft start-ups. With a soft starter, the starting of the driven machine can be more gently and thus avoid unnecessary shocks to the grid or other devices.

Pump sequential circuit

Many pump applications have several pumps in parallel in the same circuit. Pumps in plants with a flat characteristic (high static pressure, e.g. water supply, sewage treatment plants) often work between lower and upper reservoirs, with which an accurate control of the flow is unnecessary.

However, parallel pumps require a sequential circuit in each case. This is the simplest case namely with a reserve pump for redundancy and a manual switch. If two or more pumps are also in parallel operation is a differentiated sequential circuit or follow-up regulation asked: Depending on the demand, the pumps should work as well as possible and efficiently.

Criteria can be:

- Permissible deviations of the volume flow or the feeded quantity within defined time intervals
- Operational safety (automatic replacement circuit in case of failure of a pump)
- Energy efficiency
- Even or differential the running time on several pumps
- Defined time shift of pumping operations (e.g., low tariff)
- Permitted startup operations per unit of time of each pump
- Work with frequency converters
- Maximum permissible pressure surges (especially for the start)

Procedure for optimizing control logic

1. Definition of a set of top priority conditions:

- Volume flow or delivered quantity (time course) and permissible deviations from nominal values
- Operational safety (redundancy required? For which power?)

2. Definition of a set of optimization criteria:

- Energy efficiency (efficiency of pumps and motors, minimize losses)
- Operating costs (energy, tariffs and tariff periods, stress or wear, etc.)
- Quality or uniformity of the output
- Automation or flexibility of the controller regulation; which manual interventions are possible and allowed?

3. Create control strategies and compare variants.

Use of several pumps

When planning the system, the use of several parallel pumps should be considered. In many cases this is necessary for reasons of operational safety: If a pump fails, a backup one must be available immediately. However, this should not be associated with energy disadvantages. For some types of installations, the use of parallel pumps offers energy advantages:

- Better efficiency and more precise control at high variation working range of volume flow or head
- Savings from frequency converters for volume control

Depending on the type of investment, structural and technical components can be flexibly combined. Storage tanks (in open plants) or membrane pressure tanks (pressure increase) allow a gradual operation in sequential circuit or an interval operation of the pumps. The respective control regulation of the entire system is already at the planning of structural measures and hydraulics.

Speed variation

The speed variation allows operating points with lower volume flows to set lower production levels. A motor with variable speed brings proper use in the following advantages:

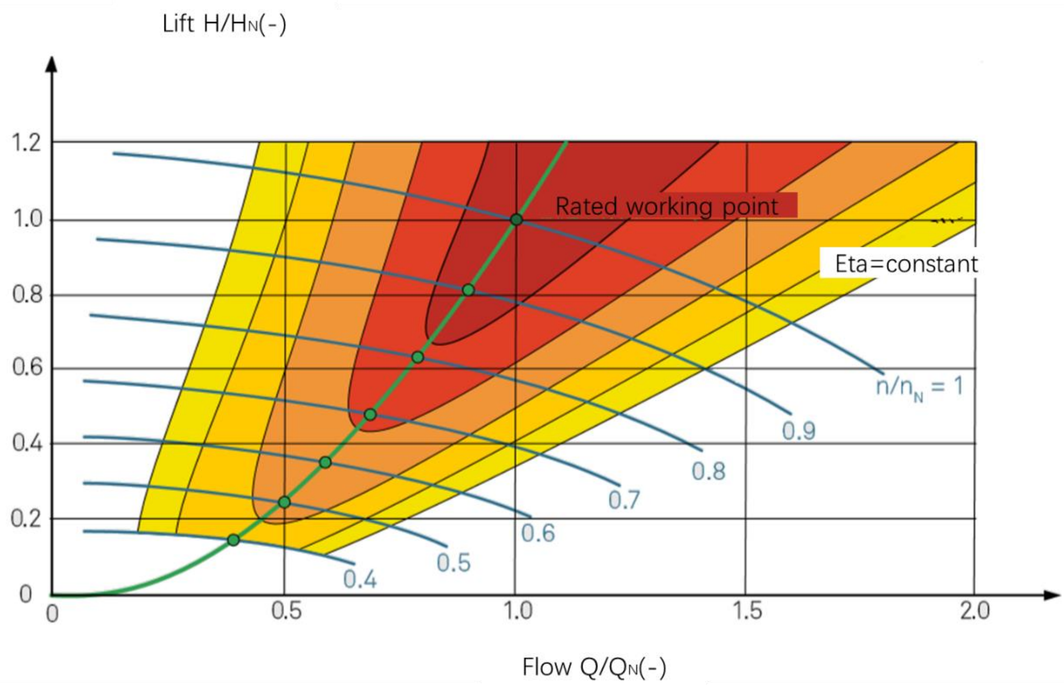
- Energy saving
- Speed control allows constant operating conditions.
- Soft start, which reduce the thermal and mechanical damage of the wearing
- Lower payloads
- Reduced shaft deflection
- Lower maintenance costs

Use of series or parallel pumps:

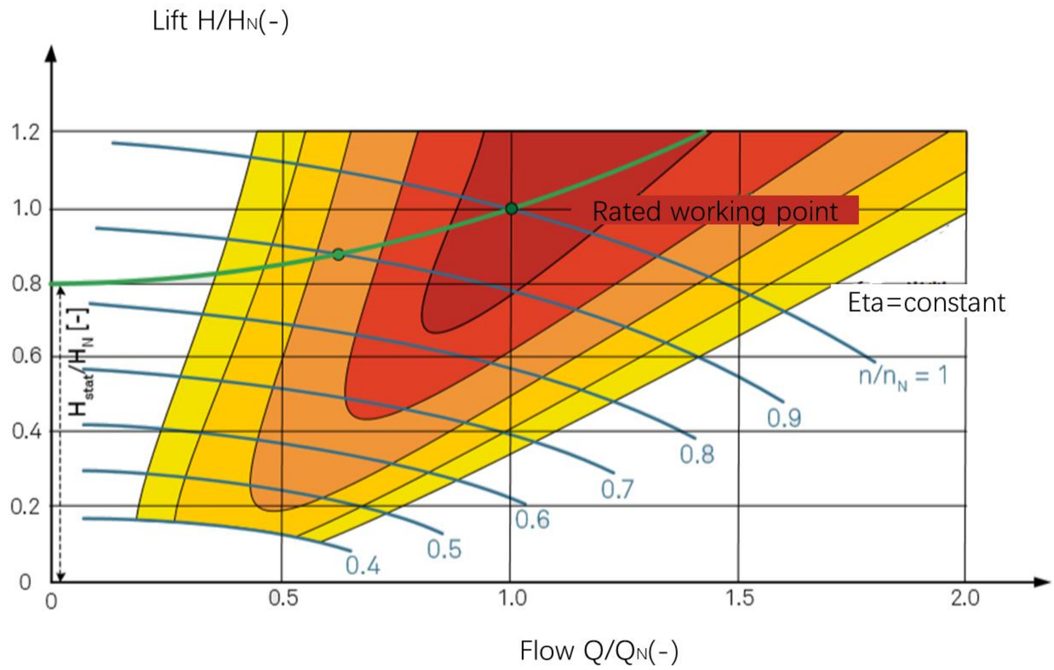
- With parallel running, pumps can work at constant delivery head and the volume flow can be doubled. It should be noted that the pressure losses will increase with the square of the volume flow increasing rate.
- All parallel pumps equipped with capacity of speed variation makes no sense. It is sufficient if one or two pump motors are controlled by frequency converter.
- As long as one pump meets the operation requirements, parallel pump operation should be avoided, except when high peak demands in short time is required (for example, firefighting).

The ideal usage of variable displacement pumps is for systems with broad and variable volume flows and low static head system curve (Figure 9). It is not suitable to apply the variable speed in systems with high static head (Figure 10). Pay attention to variable speed pumps especially in systems with:

- Large and frequent load variation
- High rated power
- Operating time of more than 2000 hours per year.



Variable speed results in a large system characteristic changes without or low Hstat.



Variable speed makes no sense at flat system characteristic (predominant Hstat).

4. Assessment and optimization of old plants

The five most common defects in plants:

- Oversized motors and pumps work in bad operating point.
- Throttle control instead of closed-loop control with frequency converter
- Operation without benefit, no timeout
- Unnecessarily large flow and delivery head
- Old inefficient motors and pumps

4.1 Evaluation of existing pump systems

pump

- Evaluating pumping systems can locate inefficient points and estimate the energy saving potential.
- The rating of a pump system is given for operation, pump curve, volumetric flow, system pressure, number of revolutions, number of stages and characteristics of the fluid.
- To increase efficiency, unnecessary pumps should shut down, oversized pumps are replaced or re-dimensioned and if appropriate, frequency converter for variable speed control is used.
- The load cycles of the pump in process show energy saving potential in every operating point. If a variable speed drive can be used, the optimal energy supply can be set for each operating point (only applies with high loss share in the system characteristic curve).

Losses in the system

- Control of the operating point via a throttle or a bypass will change the system characteristic to the pump, which reduces energy efficiency.
- When to use of control valves (highly inefficient) for throttle control, the higher valve opening rate has minimal pressure losses.
- Increased pressure losses from corrosion and lime scale will massively increase energy consumption.
- The pressure and friction losses depend on the diameter and length of the pipes, inner surface texture of pipes, the volume flow and the viscosity of the liquid.
- The energy saving potential can also be achieved by using software tools, such as «DOE's pumping system assessment tool ».

system maintenance

Preventive and predictive maintenance are distinguished below:

- Preventive maintenance includes coupling alignment, lubrication, maintenance and replacement of seal rings and driving motor.

- Predictive maintenance minimizes unplanned system failures. It includes vibration analysis, motor development analysis, lube oil analysis and periodic analysis.
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- General maintenance checklist
- Check for leaks
- Check the mechanical seals
- Control of the bearings
- Control of vapor bubble damage (cavitation)
- Motor and pump alignment
- Condition of the motor

4.2 Determine the energy efficiency of the pump used

Tests help to identify inefficient systems and to identify energy saving potentials. System installed measuring instruments or mobile devices can be used for testing. Measured data can be used to evaluate measures to optimize pump efficiency:

- Cleaning the system
- Revision of the pump, replacement of damaged bushings, seals, impellers, etc.
- Replacement of the pump or retrofitting with a frequency converter.

Measurements on pumps

- Evaluation of the information on the nameplates of the pump and motor (manufacturer information)
- Determining the input power: electrical measurement
- Determining the output power: measurement of volume flow and pressure difference