VARIABLE SPEED TRANSMISSION GEARBOX, THE SOLUTION FOR YOUR DYNAMIC DRIVE PROBLEMS

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ABSTRACT

Production during dredging is mainly determined by two factors: how much can I cut away and how much of the excavated soil can I transport hydraulically. We have to do with two separate processes. The excavation of the soil with the cutter installation in combination with the fore side winch and the transportation of the soil by means of the hydraulic installation consisting of the dredge pump, the pipe lay out and the drive of the pump.

Common element of these two installations is the suction line and especially the suction mouth, which is placed in the cutter. The flow sucked up by the suction mouth determines the concentration of the mixture in the pipeline and the spill of the excavation process. A low flow results in a high concentration, which is positive for the hydraulic transport, but a too low flow results in an increased spill and finally in a drop of the total production.

For the cutter process and the hydraulic transport automation is developed which controls some parameters in such a way that the efficiency of the process is optimised.

In the whole transport process several separate processes can be distinguished, whose efficiency depends on different criterion.

The question about the definition of efficiency occurs. We can transport with minimum energy costs, with minimum total costs, maximum profits, minimum wear, minimum overflow losses, minimum risk for damage, etc. Depending of the choice of the optimum one or more parameters should be controlled. Efficient dredging requires accurate information on the hydraulic dredging and transport process.

This publication describes the separate processes with their optimisation criterions. Where is the optimum of a process and why is that an optimum. How to realize that the working point of the pump-pipeline combination stays in this optimum point.

As a solution for the automation of the hydraulic process this paper describes the VARIBLOCK, a gearbox made by IHC with a continuously variable transmission ratio. The gearbox controlling system enables reactions on other process parameters such as: vacuum, discharge pressure and dredge mixture velocity.

Keywords: Dredging, slurry transport, centrifugal pump, efficiency, automation, gearbox

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INTRODUCTION

In theory the working point of a hydraulic transport system is determined by the intersection, in the Q-H diagram, of the pump characteristic and the pipeline characteristic. In this point there is equilibrium between available pressure from the dredge pump and required pressure from the pipeline system. The pump characteristic is the combination of the characteristic of the centrifugal pump and the characteristic of the drive. The most important system parameter is how pressure head varies with slurry flow rate, depicted by the system curve.

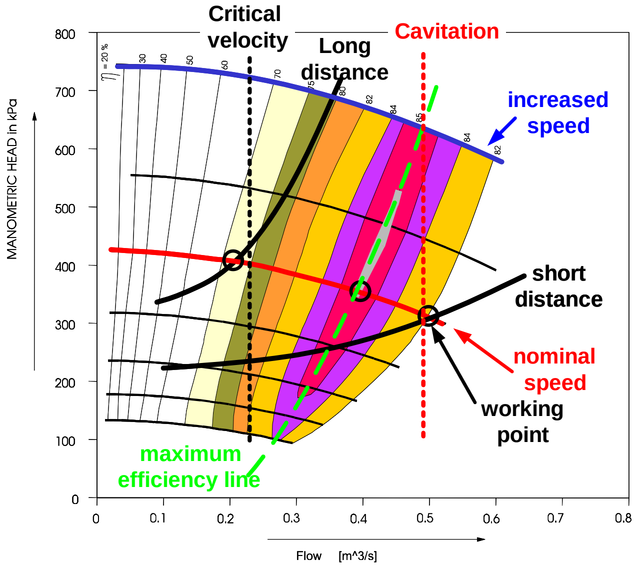

Figure 1. Working area

Several parameters have an affect on the position of this working point and a variation in one of these parameters results in a change of the working point. Therefore a dredge pump, and also the drive, must be capable of spanning a large number of potential working points, which to gather a working range. Important differing parameters in the dredging process are the average grain size diameter of the soil (coarse or fine), the length of the pipe line (short or long), the concentration of the mixture (low or high), the dredging depth (large or un deep) and the facilities on the deposit (see Figure 1).

The affect of these parameters can be minimised by automation of the process. A process with fewer variations in the parameters usually results in a higher average output compared to a process with larger fluctuations. Question remains about the purpose for the control and which parameter(s) will be controlled. There are many things valuable for automation:

- working around the critical velocity;
- working close to the decisive vacuum;
- transporting with minimum energy costs;
- transporting with minimum total costs;
- transporting with maximum profits;
- transporting with minimum risk for failure;
- transporting with minimum wear.

Usually working around a desired point requires an automation of the drive of the dredge pump. The affects of most of the variations inherent to dredging can be dealt with variation in the speed of the drive or only the speed of the impeller. Optimising the dredging process demands control of the speed of the dredge pump.
Continuously variation of the speed is possible by continuously variation of the transmission ratio of the gearbox between drive and pump. Important for a variable speed drive is that it can be effected automatically, without pump shutdown, with essentially no power or speed limitations and with relatively quick response time.

This paper describes a gearbox with a continuously variable transmission ratio, making it possible to position the working point on each desired flow-head ratio. This can be the point with minimum fuel consumption, minimum wear of the engine or dredge pump, maximum efficiency of the dredge pump and no limitations by cavitation. The gearbox controlling system enables reactions on other process parameters such as: vacuum and dredge mixture velocity. This revolutionary gearbox concept has been named; IHC Variblock.
Successively different processes will be discussed.

DIFFERENT PROCESSES.

The cutting process

The output of a dredger is clearly governed by the quantity of material cut away, or in the case of sandy soil, dislodged per unit of time. The dredging process starts with the disintegration of the soil by disturbing the cohesion between the particles. For loose packed, free running material, the flow generated by the dredge pump is enough to break the cohesion between the particles by erosion and to pick up the suspended material. The total flow around the suction mouth has a strong affect on the production. This method of excavation will be used by plain suction dredgers.

Figure 2. Cutting the soil with a cutter

For cohesive material and compacted sand and gravel cutting tools like high pressure water jets, a cutter head (see Figure 2) or bucket wheel are required. Important in the suction process is the balance between the cutting tool production and pump capacity. Inside the hydraulic process the mixture velocity is the tool for controlling the production.

The cutting tool production follows from: $Q_{situ} = a \cdot b \cdot v_s \cdot (1-\eta)$ m^3/s

With: a advancement or step in m; b the vertical change in depth in m; v_s the swing speed in m/s and η the spill. Spill is the percentage of material that is excavated by the cutter but not picked-up by the suction mouth. The amount of spill depends on many parameters, such as:

- The height of the breach;
- Step length or advancement of cutting tool;
- The rotational speed of the cutting tool;
- Construction of the cutter, particularly the angle of cutter blades;
- Swing speed of the cutting tool;
- Soil type;
- Mixture velocity around the suction mouth.
- Distance between suction mouth and bottom

With a constant cutting tool production, an increase in the mixture velocity results in a lower concentration and lower spillage. A decrease in mixture velocity results in a higher concentration and higher spillage.

The total amount of mixture picked-up by the suction mouth consists of in situ material and extra water, necessary for the transportation of the solids.

The production follows from: $Q_{situ} = \frac{\pi}{4} \cdot D^2 \cdot v_m \cdot c_t$ m^3/s , where:

Q_{situ} is the flow in situ material in m^3/s; D is the diameter of the pipe in m; v_m is the average mixture velocity in m/s and c_t is the volumetric concentration of in situ material. When the amount of soil excavated by the cutting tool equals the soil picked-up by the pipeline, the concentration follows from:

$$c_t = \frac{a \cdot b \cdot v_s \cdot (1-\eta)}{\frac{\pi}{4} \cdot D^2 \cdot v_m}$$

The relation between the mixture velocity, concentration and spill is given in Figure 3 for a constant cutting tool production.

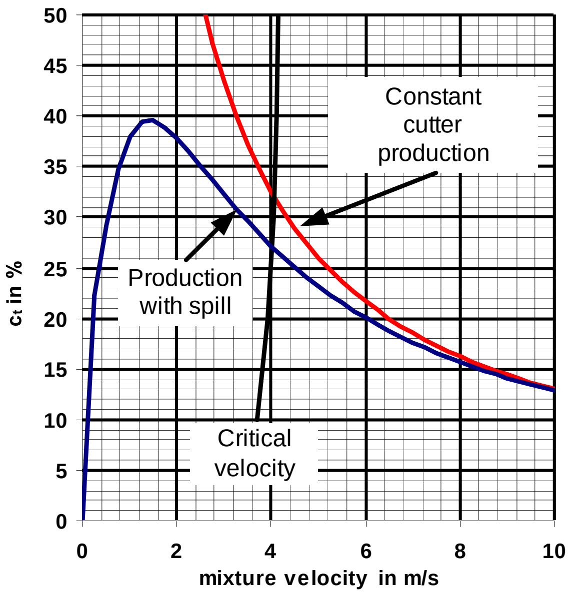

Figure 3. Minimum operating velocity

Conclusions from this figure are:

- High mixture velocity at constant cutting production gives a lower concentration and a low mixture velocity results in a higher concentration but also in more spill;
- An in situ material concentration up to 40% is possible and also noticed in practice;
- For the example in figure 3 the optimum velocity is around 2 m/s. For lower velocities the spill increases to 100% and the pipeline production to zero. The optimum velocity can be used as a set point for the automation of the dredge pump. Further on in this paper it will be explained why we prefer a low velocity.

Input for the automation is the mixture velocity and the mixture concentration. Maximizing of the concentration will be realized by reducing the mixture velocity till a limit velocity has been reached. In practice this will be achieved by speed control of the dredge pump.

Critical velocity

The critical velocity is the minimum velocity required to transport a solid material through a pipe line without any particle deposition. This means that the particles in the mixture remain in suspension.

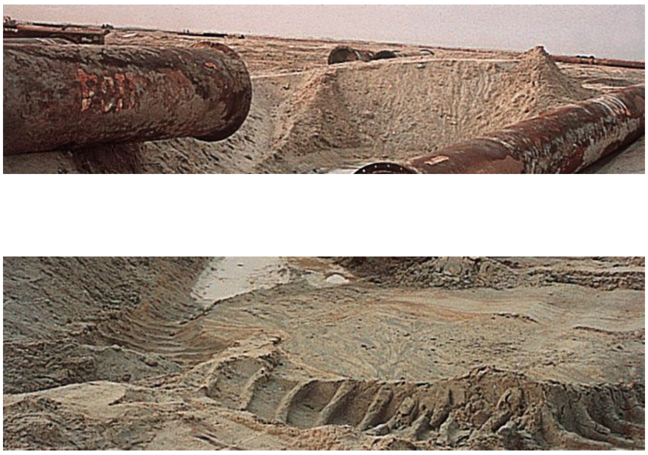

Figure 4. Depot in a pipe line

If the velocity falls below this critical value, sedimentation occurs in the pipeline indicating that the velocity has become sub-critical. The moment the velocity is decreased too much, all the solids entering the pipeline will deposit, resulting in an ultimate hold-up and the pipeline starts to clog. (see Figure 4). It is, of course, evident that one should never choose such a low velocity that the pipe line threatens to block, causing stagnation so that the dredge master feel compelled to pump extra dilution water, thus harming the production.

The critical velocity is determined by a number of factors, among which are the pipe diameter, the nature of the soil being transported (average grain size and grain size distribution, shape and density of the grain), the density of the mixture and the length and slope of the straight section of the delivery pipe.

The smaller the margin between the critical velocity and the actual velocity of the mixture, the lower is the resistance in the pipeline. This implies that the resistance is minimal at a velocity which lies just above the critical value and in this respect it is attractive to work at lower velocities, while low resistance means also low Specific Energy Consumption (SEC).

Disadvantage of working around the critical velocity is the occurrence of sliding and stationary beds of particles. Substantial pipe abrasion may occur in the sliding bed regime and low transport efficiencies are characteristic for both situations. A low transport efficiency results in a reduction of the transport concentration and therefore in a lower production. For this reason slurry pipelines must be designed and operated at a safe margin above the critical velocity, the so-called minimum operating velocity.

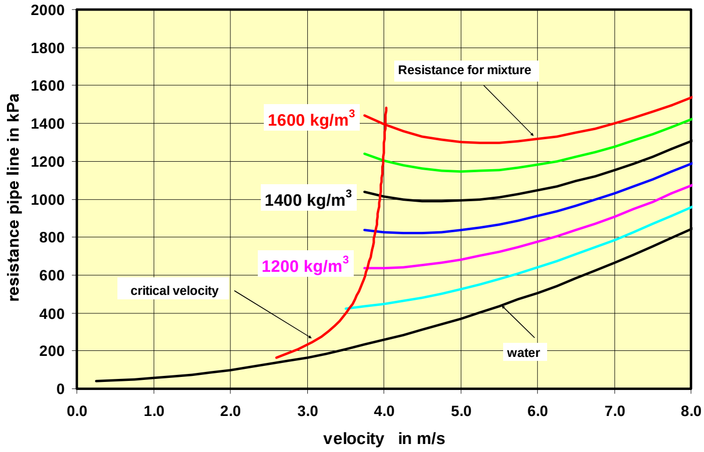

Figure 5. Critical velocity in a pipe Ø 700 mm

In Figure 5 the minimum operating velocity is given for moderately coarse sand (average diameter of 0.236mm) in a pipe with a diameter of 700 mm. From this figure it will be clear that for this material, velocities below 4 m/s can result in problems.

The critical velocity for moderately coarse sand (about 4 m/s) is also given in Figure 3, and this velocity is higher than the optimum velocity of 2 m/s. For this situation the critical velocity is the limiting factor in the hydraulic transport and the maximum attainable concentration is limited to about 27 % material in situ. For finer material the critical velocity will be lower and, according to Figure 3, the concentration can be more.

Input for the automation will be the maximum value of the critical velocity and the optimum velocity.

Working around the critical velocity means working with a nearly constant flow, which depends on the type of soil. When the soil is constant for a long period it is possible to calculate the critical velocity and use this value as input for the automation. By variable soil type it is possible to use a grain size estimator, which is based on up-to-the-minute measured data from the dredging process, and to use this estimator for the calculation of the critical velocity.

In practice, keeping the mixture velocity constant will be achieved by speed control of the dredge pump.

Constant flow is also important for the feed to a processing plant. The dredging capacity of the suction dredger must be adjusted to the maximum capacity of the controlling plant and the more constant the flow the higher will be the efficiency of screens and other separation tools.

Specific Energy Consumption.

Another important process parameter is the cost for energy, and especially the cost per m^3 transported material. This is the so-called Specific Energy Consumption (SEC). The required energy consumption follows from the pipeline resistance (Δp) and the mixture flow (Q). By using a generalized model for the pipe line resistance, the energy consumption follows from:

$$P = \Delta p \cdot Q_m = \varepsilon \cdot \frac{1}{2} \cdot \rho_m \cdot v_m^2 \cdot \frac{\pi}{4} \cdot D_l^2 \cdot v_m = c_1 \cdot \rho_m \cdot v_m^3 \quad \text{(kW)}$$

Where: Δp is the total pipe line resistance, Q_m flow in m^3/s, ε is total resistance factor for the pipe line, ρ_m is the mixture density in kg/m^3, v_m mixture velocity in m/s, D_l pipe line diameter in m and c_1 is constant.

The production on solids follows from: $$Q_s = \frac{\pi}{4} \cdot D^2 \cdot v \cdot \frac{\rho_m - \rho_w}{\rho_s - \rho_w} = c_2 \cdot v \cdot \frac{\rho_m - \rho_w}{\rho_s - \rho_w} \quad (\mathrm{m^3/s})$$

and the SEC can be defines as : $$SEC = \frac{P}{Q} = \frac{c_1 \cdot \rho_m \cdot v_m^3 \cdot \left(\rho_s - \rho_w\right)}{c_2 \cdot v_m \cdot \left(\rho_m - \rho_w\right)} = \frac{c_3}{1 - \frac{\rho_w}{\rho_m}} \cdot v_m^2 \quad \left(\frac{\mathrm{kW}}{\mathrm{m^3/s}} \, or \, \frac{\mathrm{J}}{\mathrm{m^3}}\right)$$

Where: ρ_s density solids, ρ_w is density water and c_2 and c_3 are constant.

Conclusion from this formula is that the SEC is minimal at lowest velocity and decreases with the concentration. In practice pipe line resistance is more complicated than assumed in the formula, resulting in a SEC just above the critical velocity.

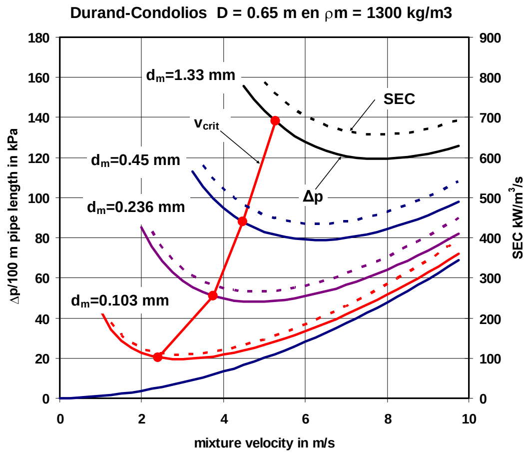

Figure 6. Specific Energy Consumption

For the determination of the pipeline resistance and the Specific Energy Consumption calculations are carried out for four different types of soil with a mixture density of 1300 kg/m^3 and a discharge distance of 100 m. The results from the calculations are given in Figure 6, together with the critical velocity according to MTI. The difference between the deposition-limit velocity and the velocity of minimum friction loss is very small in the fine slurry flow. The operation is safe enough and the SEC the lowest at a velocity just above the critical velocity. In the coarse flow the difference becomes bigger, but the conclusion is the same.

Working just above the critical velocity results in a minimized SEC while, caused by the low mixture velocity also wear is minimized. For a given power the amount of sand one gets through a pipe line is greatest at this optimum velocity. The secret of successfully transporting solids by the hydraulic method lies in using a minimum of energy and a minimum velocity, just sufficient to achieve the desired result, but no more than that, in order to keep the operating costs as low as possible.
The optimum velocity is the input for the automation. For working around SEC the same method of automation can be used as was suggested for working around the critical velocity. In practice, keeping the mixture velocity constant will be achieved by speed control of the dredge pump.

Maximum profit.
What happens when not alone the costs are important but also the profits? Depending on the price for one m^3 sand it is worth considering transporting with a higher velocity than the critical or optimum velocity (for SEC).
If in the total exploitation of the slurry installation costs for energy are of minor importance and also more wear is acceptable, a higher mixture velocity can result in more production and therefore in more return on investment. Higher productions become also important in the situation that the completion date of a project threatened to exceed.
Of course under the condition that more material will be excavated by the cutting tool. When this is not possible a higher velocity results only in a reduction of the concentration and more energy consumption per m^3 material.

The cost distribution for a trailing suction hoper dredger is given in Figure 7. The fixed costs, which are independent of the mixture velocity, (capital, crew, insurance and incidental expenses) amount 60% of the total costs and the variable, velocity related costs such as repair and maintenance and fuel (or other energy source), amount 40%. These ratios are only valid for a certain production of the dredger. A larger production results in a larger percentage for repair and maintenance and fuel.

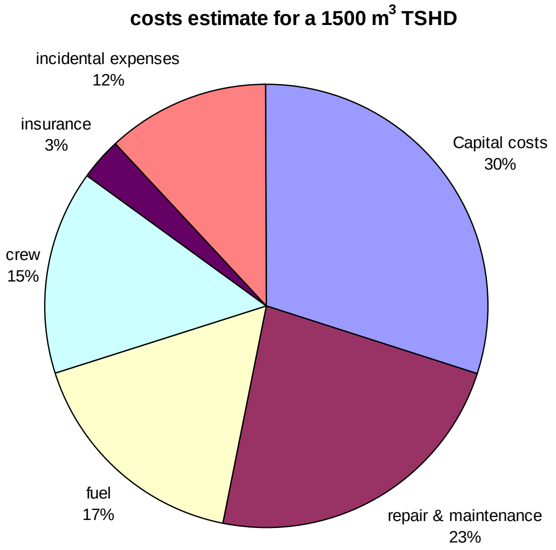

Figure 7. Distribution of costs

The revenues per hour follow from: $P_{rev} = \frac{\pi}{4} \cdot D_p^2 \cdot v_m \cdot c_t \cdot 3600 \cdot €_{m^3} = A_0 \cdot v_m \cdot €_{m^3}$ €/h

Where: P_{rev} is the revenue in €/hour, D is pipe line diameter, v_m mixture velocity, c_t the volumetric concentration of solids, €/m^3 is the amount got for 1 m^3 material in situ and A_0 is constant.

The costs follow from: $C_{costs} = C_{fixed} + C_{rep\&main} + C_{fuel} = €_{fixed} + €_{rep\&main} \cdot A_1 \cdot v_m^3 + €_{fuel} \cdot A_2 \cdot v_m^3$ €/h

Where:
- C_{costs} are the total costs for the transport installation in €/h;
- C_{fixed} are the costs for capital + crew + insurance + incidental expenses in €/h;
- $C_{rep\&main}$ are the costs for repair and maintenance in €/h, consisting of the unit price $€_{rep\&main}$ in €/h, A_1 is constant and v_m is the mixture velocity
- C_{fuel} are the costs for energy in €/h, consisting of $€_{fuel}$ as the price per unit of energy and A_2 is constant

Figure 8. Replacing an impeller

For simplification it is assumed that repair and maintenance are very strong correlated to the wear ($\sim v^3$). In practice the situation is more complicated while the costs for repair and maintenance consist of the costs for spare parts, cost of labour and downtime (see figure 8). Costs for fuel are correlated to power or energy consumption ($\sim v^3$).

For a certain situation the fixed costs ($€_{fixed}$) are about 60% of the total costs, repair and maintenance ($€_{rep\&main}.A_1.v^3$) about 23% and fuel ($€_{fuel}.A_2.v^3$) about 17%. The optimum situation is where the difference between revenue and costs (is profit) has reached its maximum value.

This follows from: $€_{max} = P_{rev} - C_{costs} = A_0 \cdot v_m \cdot €_{m^3} - €_{fixed} - €_{rep\&main} \cdot A_1 \cdot v_m^3 - €_{fuel} \cdot A_2 \cdot v_m^3$ €/h

The maximum follows from: $\frac{\partial \in_{max}}{\partial v_m} = A_0 \cdot \in_{m^3} - 3 \cdot \in_{rep\&main} \cdot A_1 \cdot v_m^2 - 3 \cdot \in_{fuel} \cdot A_2 \cdot v_m^2 = 0$ €/h

or : $v_m = \sqrt{\frac{A_0 \cdot \in_{m^3}}{3 \cdot \in_{rep\&main} \cdot A_1 + 3 \cdot \in_{fuel} \cdot A_2}}$ m/s This relation is given in Figure 9.

This figure shows that with increasing price for 1 m^3 solid the optimum velocity for obtaining a high profit is also increasing.

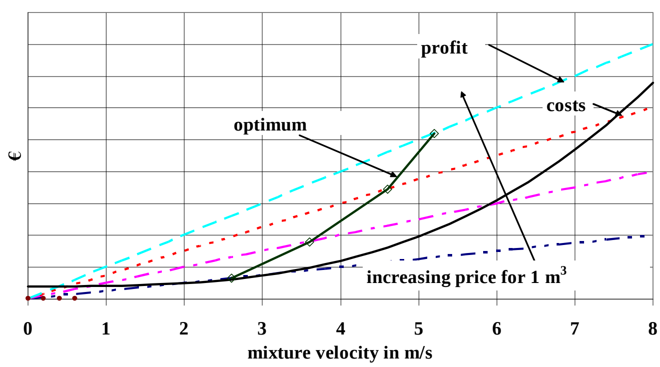

Figure 9. Optimum velocity for maximum profit

It will be clear that previous calculations are indicative. The idea that higher prices for one m^3 permit higher mixture velocities is important. To find this optimum it is necessary to make a good exploitation analysis from the dredger so that the costs as a function of the velocity are well known. Working around the optimum velocity means working with a variable flow, which depends on the type of soil and the amount got for 1 m^3 solid. When the soil is constant for a long period it is possible to calculate the optimum velocity and use this value as input for the automation. By variable soil type it is possible to use a grain size estimator, which is based on measuring data from the dredging process, and to use this estimator for the calculation of the optimum velocity.
In practice, controlling the mixture velocity will be achieved by speed control of the dredge pump.

Cavitation in the pump.
Previous examples are related to the lower limit of the velocity in the system. Figure 1 shows that there is also a upper limit at high flow rates, the flow rate corresponding to the decisive vacuum of the pumping installation and suction pipe concerned. This limitation is called the cavitation limit and flow rates in excess of this must be avoided.

Figure 10. Boiling water "cavitation" in an impeller

At a certain velocity, and depending on many other parameters, the static pressure on the suction side of the pump falls below the saturated vapour pressure of the transported liquid and the liquid starts to boil (see Figure 10). At the onset of cavitation, the discharge pressure deviates from the original Q-H curve. Increasing cavitation, the so-called fully developed cavitation, leads to a further grow of the vapour bubbles and the bubbles modify the flow patterns in the system. Under these conditions losses increase and performance rapidly deteriorates. Eventually the cavities or cavitation bubbles become large enough to choke the passageway and the pump chokes. The solids yield and the discharge pressure deteriorate and the flow rate rapidly drops to zero.

The vapour bubbles are entrained in the flow and carried to the impeller, where the pressure increases above the saturated pressure, causing the bubbles to implode abruptly. This process may be accompanied by hissing and rattling, severe vibration, fairly heavy shocks and other irregularities. Furthermore cavitation causes wear and damage to the pump parts, especially the impeller (see Figure 11). Cavitation can be considered as the upper limit of the hydraulic transportation process.

Figure 11. Impeller with cavitation erosion

The effect of cavitation on the transport process results in a limitation of the maximum flow and/or density. At high flows a point of intersection between normal pump and pipe line characteristics no longer exists. Working at the original working point is not longer possible. Cavitation is related to the pressure drop over the suction line. This also influences production.

This dependence can be demonstrated with the aid of a simple suction formula:

$$vac = \varepsilon \cdot \frac{1}{2} \cdot \rho_m \cdot v_m^2 - \rho_w \cdot g \cdot D + \rho_m \cdot g \cdot (D-a) \quad \text{kPa}$$

Where :

- Vac is the total pressure difference over the suction line in kPa. Vac depends on the dynamic losses, related to the velocity and the density of the mixture, and the static head related to the suction depth and the position of the dredge pump. The static head is the pressure difference between the water column outside the dredger, which depends on the dredging depth (D), and the mixture column in the suction line, which depends on the dredging depth (D) and the position of the pump in relation to the waterline (a).
- ε is the total resistance coefficient for the suction line, consisting in losses for acceleration, entrance losses, straight pipes, bends and hoses.
- ρ_m is the density of the mixture in kg/m^3;
- v_m average velocity of the mixture in the pipe line in m/s;
- ρ_w is the density for water (fresh are salt) in kg/m^3;
- D is the total actual dredging depth in m;
- a is the position of the centre of the dredge pump in relation to the waterline in m.

The limit of the process occurs when the pressure drop over the suction line equals the decisive vacuum of the pump. The decisive vacuum is deemed to be the vacuum at which the manometric head differs 5% from the normal manometric head at the same pump speed.

For a certain value of the decisive vacuum (say 80 kPa) calculations are carried out for a dredger with a suction diameter of 700 mm, dredging depth 18 m and the pump on waterline and 3 m below waterline. The soil is moderately coarse sand with d_m= 0.236 mm. From the previous formula one can calculate the relation between velocity and density.

The production on solids follows from: $Q_s = \frac{\pi}{4} \cdot D^2 \cdot v_m \cdot \frac{\rho_m - \rho_w}{\rho_s - \rho_w}$ (m^3/s)

The results are given in Figure 12, including the restrictions caused by the critical velocity and the cutter production.

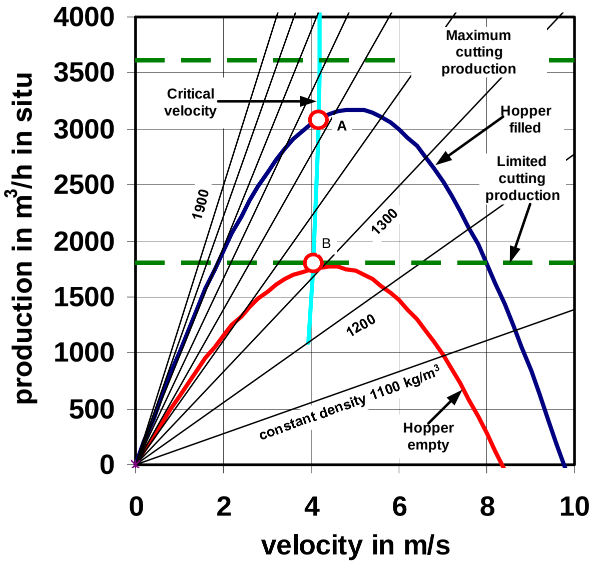

Figure 12. Restrictions caused by cavitation

The curved line in the figure is the maximum production, limited by cavitation. Realization of the maximum production is possible by working at the decisive vacuum of the pump and then to reduce the velocity of the mixture till the maximum production has been reached. Keep this velocity as constant as possible. It is possible that the critical velocity is larger than the velocity for maximum production. In this situation the critical velocity will be the limiting factor in the process (point A in Figure 12). Figure 12 demonstrates very clear the affect of the position of the pump in relation to the water line. Only 3 meter difference in the position of the pump-inlet results in a theoretical difference in production of about 80%

When the production will be limited to the cutting production then the maximum production is always around the critical velocity (point B in Figure 12).

Reasons for working around Best Efficiency Point.

From experience with pumps it is known that for each design only one point exists on its characteristic curve where the efficiency is at its maximum. The design characteristics for both performance and reliability are optimized around this point designated as the Best Efficiency Point of the pump and mostly it will be the design point of the whole transport installation (see figure 13).

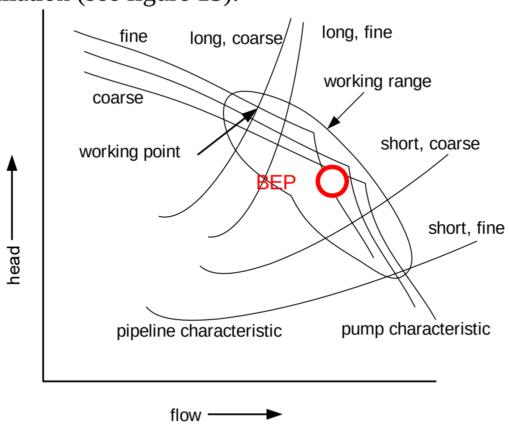

Figure 13. Variation around the Best Efficiency Point

Sometimes a pump operates at a capacity slightly above or below the Q_{BEP}. It is unusual to operate continuously at a capacity at which the efficiency is much below the maximum value. It is common practice to position the point of intersection between pump characteristic and pipe line characteristic as close as possible to the Q_{BEP} or to the flow rate with maximum efficiency for that speed. For that situation the flow through the pump is optimal. The flow through the impeller and diffuser is uniform and free of separation, and is well controlled. The mixture enters the impeller vanes and casing diffuser in a shock less manner and the hydraulic efficiency is maximum.

When it is possible to control all the process parameters such as grain size, fixed discharge distance, flow and concentration then it is also possible to optimize the pump and pipeline combination. This can occur during slurry transport with a feeder and slurry preparation. During dredging there is always a variation in the soil, the dredging depth, the mixture concentration and the discharge distance. Working away from the design point is inherent to dredging.

Variations in soil, dredging depth, concentration and discharge distance results in a variation in the pipe line resistance and in the available pump pressure. The consequence of these variations is a change in the point of intersection between pump characteristics and pipeline characteristic (see Figure 13). A dredger can work on a short or a long distance, in fine or coarse material and a pump can work at different speeds. This last is usual during trailing and discharging of a trailing suction hopper dredger. The result of these variations is a shift from the working point and the working point does not longer coincide with the design point. What are the consequences from working away of the BEP?

Generally, the impeller, the diffuser or casing and/or the volute tongue or cutwater are designed for the same design flow rate. The flow rate for the design of the impeller inlet may be greater or less because for the design of the inlet also recirculation and cavitation has often to take into account. As soon as the operating flow rate departs from the design flow rate, variations of the fluid flow incidence at the leading edge of the blades occur.

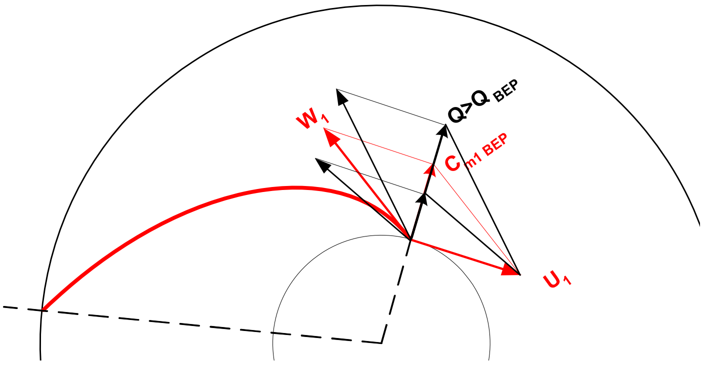

Figure 14. Variation in velocity

Off-design conditions are first of all characterized by mismatching between inlet blade angles and local fluid flow angles. As it can be seen in figure 14, the relative velocity at inlet becomes more and more tangential as the flow rate is reduced. For a flow rate equal to Q_{BEP} the entry of the flow into the impeller is shock less, the relative inlet velocity vector is tangential to the first element of the impeller blade. For a flow rate $Q<Q_{BEP}$ impingement on the leading face of the vane takes place and eddies occur on the trailing face of the vane. When the flow rate becomes to low reverse flow or recirculation occurs in some parts of the pump, resulting in a reduction of the available net positive suction head (NPSH) at the vane inlet. Keeping the velocity constant gives the possibility to work with maximum suction properties of the pump. This means less cavitation erosion and higher productions for situation where the decisive vacuum is the limit in the process.

Centrifugal and vertical pumps typically exhibit a minimum vibration near the BEP, with increases at higher and lower capacities. The vibrations spectra are dominated by harmonics of the rotation frequency (depends on number of blades). For pumps with a drive input above about 1000 kW and high specific speed, however, the forces due to flow recirculation at the impeller entry may, even at 25 to 35 % of the BEP flow rate, be so great that excessive vibration is excited in the pump and pipe work. Higher minimum flow rates are necessary for such pump sizes.

For a flow rate $Q>Q_{BEP}$ impingement on the trailing face of the vane takes place and eddies occur on the leading face of the vane. The change in flow has consequences for the performance of the pump. Mismatching induces additional losses which are referred to as incidence losses and they affect the hydraulic performance of the pump: efficiency, total head, NPSHR , radial impeller load and wear.

For flows around the BEP, the NPSHR has its minimum value. For flows above the BEP, the NPSHR sharply increases with the flow rate as a result of the increase in the velocities and the pressure distribution effects at impeller inlet.

There is also a limitation for the maximum flow rate. The highest velocity in a pump usually occurs in the throat area of the volute. At high flows the velocity head may constitute most of the total discharge head. In such cases, the static head may drop below the saturated vapour pressure of the liquid, resulting in cavitation in the outlet of the pump. Cavitation reduces the pump head and, by cavitation erosion, it reduces the life time of the pump. Summarizing: extreme high as well as extreme low flow rates have a negative effect on the existence of cavitation in a pump.

In pumps with volute casings unbalanced radial forces caused by non-uniform static pressure distribution around the outlet circumference of the impeller act on the impeller at part loads and over loads. Uniformity is only possible when there is a free vortex velocity distribution in the volute i.e. when the spiral flow from the impeller coincides with that of the volute spiral. This occurs only at the BEP and the non-uniformity increases strongly at off-design conditions.

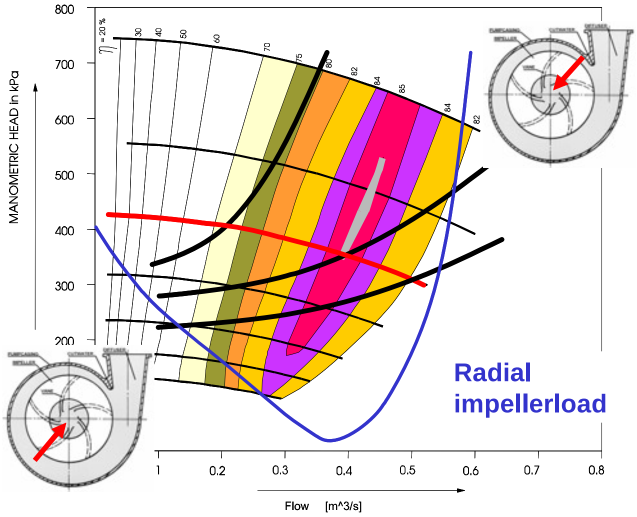

Figure 15. Variation in radial impeller load

The steady mean radial load or radial thrust acting on the impeller is characterized by a magnitude and an angular direction that is changing as the operating flow rate changes. The unsteady radial thrust can be caused by geometrical tolerances of the impeller and pressure fluctuations due to flow separation at part load. In figure 15 the curve for the radial load is given for the nominal pump speed. The mean radial thrust is mainly dependent of the type of diffuser or volute and is least in the region of the design point (BEP) and increases when the flow is increased or decreased (blue line in Figure 15, which is valid for one speed). It should be noted that there is a large increase in the thrust when $Q>Q_{BEP}$. For $Q<Q_{BEP}$ the direction of the force is “upwards” and for $Q>Q_{BEP}$ the direction of the force is downwards. The steady radial thrust is not zero at BEP.

The radial forces are of course transmitted through the shaft to the bearings and an increase of the radial thrust may lead to rapid wear of the bearings and failure of the shaft due to fatigue. Steady radial forces results in fully reversed stresses in a rotating shaft which may be increased by stress concentrations at changes in shaft cross section. Sustained operation at extremely low or extremely high flows needs the installation of a heavier shaft. It is the manufacturer’s responsibility to define flow limits where the alternating stresses in the shaft are less than the fatigue life is acceptable.

Summarizing: The mean radial load is least in the region of the BEP and increases when the flow is increased of decreased, so control from the velocity can increase the life time of the bearings and the shaft. The design point of a pump is known and the variation of this point in relation to the speed is also known (affinity laws). This information can be used as input for the pump controller.

Centrifugal pumps for the dredging and mining industry are designed to resist the dynamic contact of particles and fragments on the wearing surfaces. During this contact small parts of the construction material are cut away, this process is called abrasive erosion. The rate of wear is related to the nature of the mixture being pumped and the materials of construction of the pump. Important parameters are the grain size of the abrasive particles and the velocity of the particles or flow rate of the mixture.

An important factor for the wear rate in a pump is the operating point on the Q-H characteristics of the pump. Minimum wear will occur at or near the design point (BEP), when flow angles match the blade and cut-water angles. This results in low impact angles-provided that the solid trajectories follow the liquid flow paths- and also less turbulence due to flow separation.

At partial or over capacities the flow will not tolerate the abrupt deflection at the tongue and severe energy losses and wear are created at the vicinity of the casing throat and on the impeller.

Figure 16 shows the dramatic effect of local wear. The mean wall thickness of the pump is decreased a little, except one spot in the pump outlet. As a result of a local eddy a hole is "drilled" in the pump casing making the pump unusable. Left figure for too high flows and right for too low flows.

Figure 16. Local wear for too high and too low flow

Working around the BEP will increase the life time of many components in a centrifugal pump, e.g. the bearings, the pump shaft.

On previous pages several work situations are discussed where control of the flow or velocity will be profitable. These circumstances are:

- Working at the critical velocity for saving energy and for working at minimum costs;
- Working at a variable velocity with the purpose to maximize the profits;
- Working at minimum velocity and decisive vacuum to maximize the production of an installation which as limited by the vacuum of the pump;
- Working around the BEP for increased life time of many components in a centrifugal pump, e.g. the bearing, the pump shaft, pump impeller and casing.

CONTROLLING THE WORKING POINT.

Different solutions are possible for controlling the working point of a pump-pipe line combination; some are static and other dynamic. Static means that a new working point has been created for a longer time, it is a step-by-step variation and adaptations are permanent. Continuously variation is not possible. Static solutions are:

- Reducing the impeller diameter. Reduction of the diameter is a means whereby the pressure head, at constant speed, of an existing impeller can be lowered (Figure 17 left). The bigger the correction, the more pump efficiency suffers from adaptation. The advantage of this method is a diesel engine working again in the full torque point and at a nominal speed, but the disadvantage is that the impeller can only be used at a short distance. It is a permanent solution and makes this method not suitable for a dredger with regularly changing discharge distances and outputs.

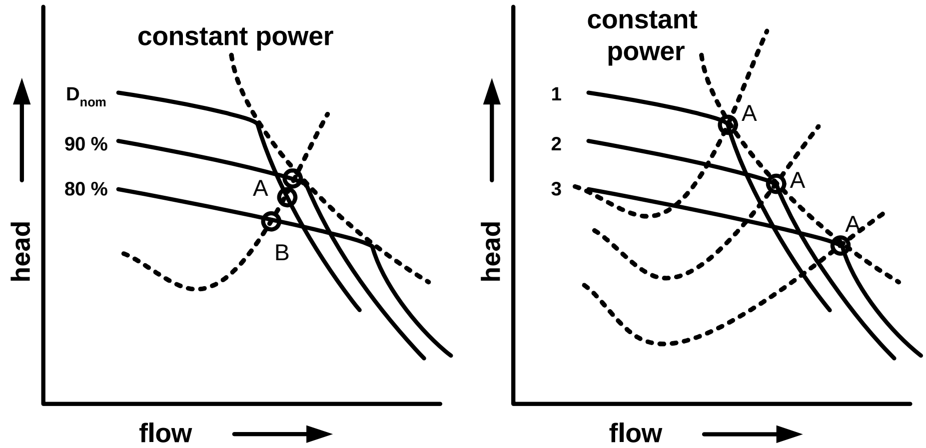

Figure 17. Effect diameter reduction and the use of a 3-speed gearbox on the working point

- Use of a gearbox with different transmission ratios. By using of a 2 or 3-speed gearbox it is possible to turn the pump at different speeds without changing the speed of the diesel engine (Figure 17 right). This gearbox is between the diesel engine and the dredge pump and has the possibility to change the transmission ratio step by step. The disadvantage of this transmission is that the ratio cannot be changed during pumping, it needs pump shutdown. An immediately reaction on variations in the dredging process is not possible.

- Changing the impeller by an impeller with different number of blades. Fitting an impeller with a smaller number of blades results in a lower pressure head and in a new point of intersection between pump- and pipe line characteristic for a longer time. The results are similar to the results with the reduced impeller; accept the efficiency which is more for an impeller with changed number of blades. An advantage of a smaller number of blades is that the passage is somewhat larger, with the result that the pump is less susceptible to blockage by debris and large pieces of stone. The disadvantage is that the impeller can only be used at a short distance; it is a permanent solution and makes this method not suitable for a dredger with regularly changing discharge distances and outputs.
- Application of a booster station results in a new working point with more head and flow. This is a very expensive solution and not suitable for a dredger with regularly changing discharge distances and outputs.

More flexible methods for controlling the working point are:

- Changing the pipe line resistance by using a variable restriction in the discharge pipe. For this solution the used power is always more than for the unrestricted pipe line, the restriction will be subject to wear and a small bore in the pipe line increases the risk for blockage of the pipe by stones. This method is not suitable for a dredger with regularly changing discharge distance and outputs.
- Changing the speed of the drive. Changing the speed of the drive (see Figure 18 left), especially when it concerns a diesel engine results in a reduction of the available power and the motor works in an area of lower efficiency. For most diesel engines speed variations are very limited, depending of the type of diesel (degree of super charging and the nature of the supercharger). A reduction of the speed results in a reduction of the flow and the pressure head. The working point changes from A to B. Within small variations of the pipe line resistance constant flow control is possible by varying the speed of the diesel.

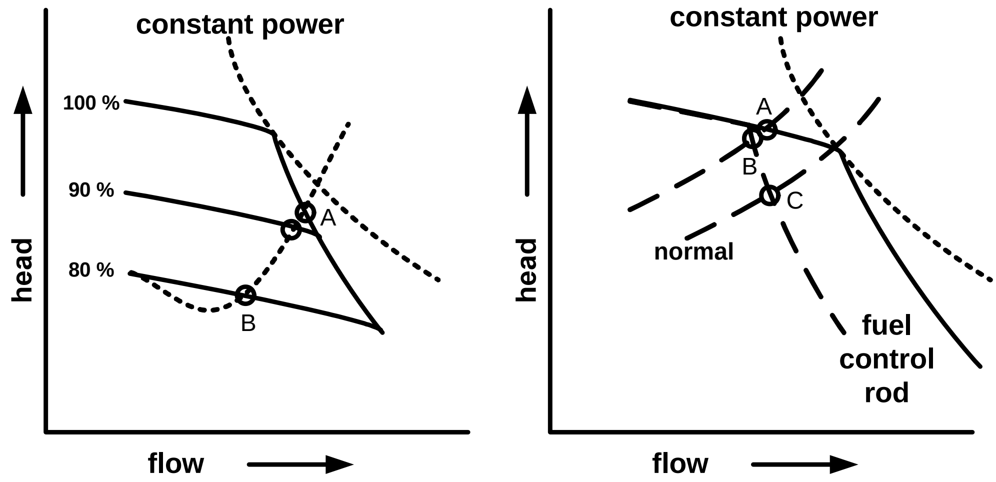

Figure 18. Effect speed variation and power variation on the working point.

- Changing the maximum fuel injection. Reducing the fuel injection (see Figure 18 right) by limiting the fuel control rod of the engine will prevent more fuel being injected to the diesel. In the pump characteristic it looks if the pump is driven by a smaller diesel engine with the same speed. This makes it possible to work in the constant torque range, which is more stable than the governor range, while the flow variations are smaller. Disadvantage is the lower flow and production to the original fuel injection.

More efficient methods for controlling the working point are:

- Application of a pump driven by a frequency controlled electric motor. Many different drive systems are available on the market and the choice depends on the requirements of the process in terms of speed control, process-automation, environment of the motor, etc. The general pump characteristic consists of a constant speed area, a constant power area and a constant torque area. The so-called electric shaft is flexible but, in general the drive requires a larger capital investment in comparison to a direct drive and the additional loss of efficiency is about 10-15 %. This is caused by the losses in the extra gearbox and the losses in the generator, electric power transmission system and electric motor. Special demands on the vessel and the crew make this solution more complex.
- Use of electronically controlled diesel engines. Modern diesel engines with computer controlled fuel injection have more or less the same possibilities as an electric drive. The pump characteristic has also a constant speed, a constant power and a constant torque area, but the range over which the diesel could be controlled is relative moderately. Only a small percentage of the speed regulation is available with constant

power, and an even smaller portion with constant torque. When the diesel engine is also driving other components, such as hydraulic pumps, generators, etc. they are also affected by the changes in speed, which can result in a variation in the RPM of e.g. the cutter or the winch.

- Application of a variable speed drive. Variation of the speed of the drive or only the speed of the impeller will be the most important parameter for optimising the dredging process. Most efficient method for controlling the speed of the impeller is possible by continuously variation of the transmission ratio of the gearbox between drive and pump. An acceptable method of varying pump speed with a constant speed prime mover has been the fluid coupling. A fluid coupling can transform the constant input speed of the diesel engine to a variable output by changing the amount of oil in the working circuit of the coupling. Variation of the volume of oil results in a variation of the slip between the two coupling parts. The slip is a measure of the inefficiency of the transmission; at off-design conditions the efficiency is rather low.

Many long pipe lines are equipped with a variable speed drive while this drive is superior in efficiency, life expectancy and availability than constant speed drives.

One of the more efficient methods to control the working point is the use of the IHC VARIBLOCK

IHC'S CONTINUOUSLY VARIABLE SPEED VARIBLOCK.

The operation principle of the VARIBLOCK is the advanced development of a proven concept. The heart of the VARIBLOCK is a special planetary gearwheel system that is driven by the diesel engine (see Fig. 19).

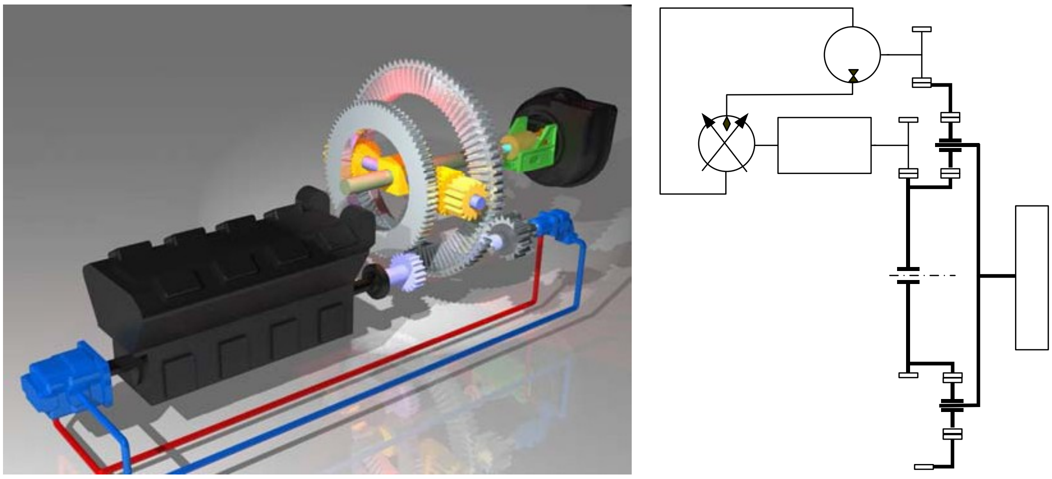

Figure 19. Control system (left) with planetary gearwheel system (right).

Between diesel and planetary gearwheel a conventional gear transmission can be used. Attached to the diesel engine is a hydraulic pump with variable volume. This pump feeds a hydraulic motor that also drives the planetary gear wheel system. When the volume from the hydraulic pump is zero, the dredge pump will have the nominal speed and this situation is comparable with the "old" full torque point of the conventional drive. The sun wheel is driven at a constant speed and the annulus will be stationary in this situation. The power flow in the hydraulic system is now equal to zero and the efficiency of the system has its maximum value.
By increasing the volume of the hydraulic pump, the speed of the hydraulic motor will increase. The speed of the sun wheel is constant again and the annulus rotates in the same direction of the rotation of the sun wheel and the output shaft. The total power is split in a power through the gears and the hydraulic power to the annulus. Both power-flows come together in the planet carrier and flow from there to the impeller. The speed of the dredge pump is increased by this action.
By reversing the volume of the hydraulic pump, the speed of the hydraulic motor will reverse. The speed of the sun wheel is constant again. The annulus rotates reverse to the direction of the rotation of the sun wheel. The annulus transports energy from the gear and via the hydraulic system this energy is supplied again to the diesel engine. The fixed unit in the hydraulic system operates now as a pump and the variable unit as a motor, they have changed their functions. The speed of the dredge pump is decreased by this action.

It will be clear that each speed can be realized by varying the volume of the pump. This speed is added to (or subtracted from when turning in the opposite direction.) the speed of the diesel engine, resulting in a higher (or lower) speed of the dredge pump. This at constant speed of the diesel engine!

The power taken by the hydraulic pump is returned by the hydraulic motor. Therefore, no energy, except for efficiency loss, will be wasted. As an example: a pump power of 1000 kW needs about 100 kW for the hydraulic system at maximum speed variation. Suppose that the hydraulic losses are 30% maximum, which means 30 kW is lost due to the hydraulic drive. With about 2% loss on gear transmission, the total losses are 50 kW, or 5% maximum. The efficiency will decrease as the variation is increased. An increase or decrease of output speed of 15% will have an overall efficiency of 94%.The highest efficiency is obtained by rotating the transmission at its design speed. As the VARIBLOCK hydraulically regulates only a part of the shaft power, the total efficiency of the gearbox transmission will still between 92-94%, much higher than other variable speed transmissions. The diesel engine can be of the simplest stationary kind, because it will give its full power at optimum speed.

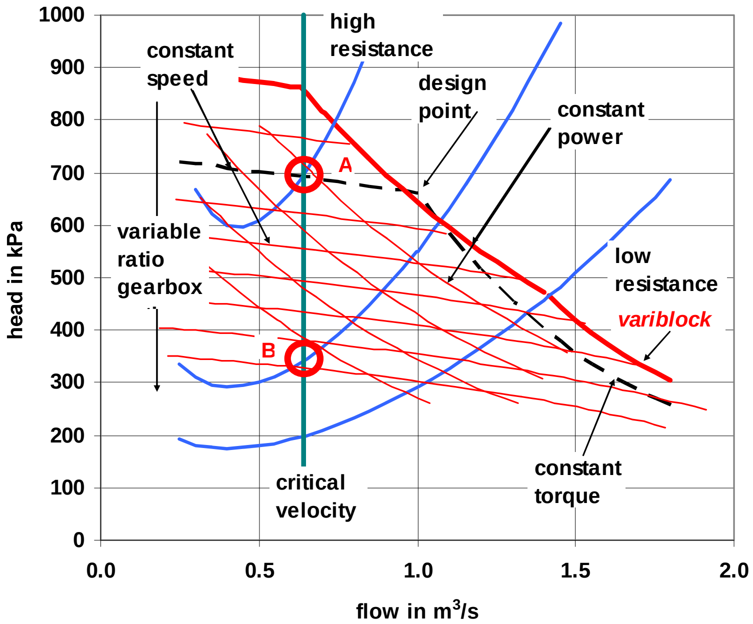

Figure 20. Pump characteristic with a Variblock

Pump characteristic for medium fine sand and a mixture density of 1200 kg/m^3. The dotted line is for a conventional direct drive with only a constant torque and a constant speed area. The drawn lines are for a pump driven by a Variblock. The pump characteristic consists of a constant torque, a constant power and a constant speed area. Compared to the conventional drive it its clear from the figure that for a short discharge distance (low resistance) the flow, and thus the production, with a VARIBLOCK, is much more than for the conventional drive. Only in a small area around the full torque point the flow with the VARIBLOCK is smaller. More important is the effect in the high speed range. With the VARIBLOCK there is more pressure available to transport the mixture with a flow above the critical velocity. This means that the same production can be realized at greater discharge distances and, maybe save a booster station.

Suppose one wants to work at constant velocity. Reasons can be a minimum SEC, maximum density, constant feed to a processing plant, etc. Suppose point A is the working point. This working point lies on the constant speed area of the conventional drive and is realized with the VARIBLOCK by varying the ratio of the gearbox. Reducing the resistance results with the conventional drive in a flow of about 1.1 m^3/s, much above the critical velocity. With the VARIBLOCK it is possible to change the gearbox ratio in such a way that the speed of the dredge pump is reduced till a lower value
With the VARIBLOCK it is possible to reduce the speed of the pump in such a way that the pump arrives at work point B. This can be realized with constant speed of the diesel engine. It is possible to realize each working point without changing the speed of the diesel engine! The diesel engine runs always in the governor range.

After that the gearbox was tested in the workshop also a test under working conditions on board of a dredger of the Dutch dredging contractor BOSKALIS was carried out. This test was very successful. A pressure of 950 kPa instead of the nominal 650 kPa could be achieved by speeding up the dredge pump. The results of the tests have been so positive that BOSKALIS ordered also VARIBLOCK's for the hopper dredgers Waterway and Coastway. Both dredgers are equipped with a VARIBLOCK that transfers a maximum of 1500 kW during dredging and a maximum of 2760 kW during pumping ashore. The field experience with IHC Variblocks has shown that the system is very robust and easy to maintain. Everybody involved with dredging practice knows that equipment, and men, operate in a rough environment. The VARIBLOCK has proved to be more than a match for these conditions.

CONCLUSIONS

- Controlling a process is important but more important is the reason why and how;
- The VARIBLOCK can control every process while the diesel engine runs in the constant speed area;
- The VARIBLOCK makes it possible to use a direct driven pump by using a diesel engine;
- With the VARIBLOCK it is not necessary to adjust impeller diameter for different lengths;
- The VARIBLOCK is for medium discharge distance a good alternative for a booster station.
- Erosion of pump and pipe is reduced with downward speed regulation, thereby increasing component life and maintenance intervals;

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