Damages on Pumps and Systems

The Handbook for the Operation of Centrifugal Pumps

Thomas Merkle

M. Eng. Dipl.-Ing. (FH)

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Copyright © 2014 Expert Verlag GmbH. Published by Elsevier B.V. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system
or transmitted in any form or by any means electronic, mechanical, photocopying,
recording or otherwise without the prior written permission of the publisher

Permissions may be sought directly from Elsevier's Science & Technology Rights Department
in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333;
email: permissions@elsevier.com. Alternatively you can submit your request online by
visiting the Elsevier web site at http://elsevier.com/locate/permissions, and selecting
Obtaining permission to use Elsevier material

Notice
No responsibility is assumed by the publisher for any injury and/or damage to persons or
property as a matter of products liability, negligence or otherwise, or from any use or
operation of any methods, products, instructions or ideas contained in the material herein

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-444-63366-8

For information on all Elsevier publications
visit our web site at store.elsevier.com

Printed and bound in Poland
14 15 16 17 18 10 9 8 7 6 5 4 3 2 1

Preface

Centrifugal pumps besides being used for transportation of pure fluids, are also very frequently used for transportation of fluids with solid components. Abrasive media drag on volutes and impellers so strongly, that considerable damages occur to the components of the pumps.

Consequently, depending on strain and composition of the medium to be pumped and the solid matters contained in it, only a low service life could be achieved and therefore being uneconomic. A wrong operation of pumps can result to cavitation and cause severe harms altogether. Under the aspects of Total Cost of Ownership (TCO) and Life Cycle Cost (LCC), this means a drastic increase of operating costs.

In this book it is described, that with suitable measures, wear up can be reduced and partly prevented. Constructive measures, preventive maintenance, optimal servicing and repair of systems or plants, can both, extend the life cycle and save expenditures.

Even the application of speed control, new technologies for overcoating and production of pump components, can also increase the profitability of pump systems considerably.

Using concrete examples, damage mechanisms and fundamental relations will be shown and evaluated. Indications for fault management as well as suggestions on measures for failure prevention and fault detection will also be analysed.

The specific wear up for example on “pumping of metal chips”, will also be described in theory and practice.

Pumps which are used in the field of shaving metal processing metal devices and machines for transportation of abrasive fluids, are oblieged to completely different operating conditions rather than those for transportation of pure, clean liquids. It will be explained, that a prognostic maintenance can be handled economically.

Deep moving, theoretical fundamentals and calculations were renounced, since many technical literature is already sufficiently available on these topics.

In this english version of my book “Schäden an Pumpen und Pumpensystemen”, I quite thank cordially Dr. Isack Majura for his support by tips and proof readings of the text. In this account, his suggestions were very helpful to write the book in a user friendly and easy reading shape.

This book is intended as a guide to be able to minimize or avoid damages. Indeed, it’s a practical help for planners, plant engineers and operators of systems in the field of shaving metal processing, as well as areas of maintenance, servicing and repair of equipment where pumps are used. Moreover, students in the fields of mechanical engineering and process engineering, it might be a helpful and valuable support for study.

Thomas Merkle
Tübingen, January 2014

1 Introduction

Damages and wear out on pumps can have very different causes. Longtime damages appear often only after years. The type and intensity of the strain of the pump has a very decisive influence on it. Short, timed operation, cyclical or continuous operation determine the lifetime of the pump indeed. Damages which occur only shortly after going into operation, are very often due to faulty planning or mismanagement. A wrongly dimensioned pump, or the operation outside the operating point, can lead very quickly to the failure or complete breakdown of the pump.

1.1 Causes and Effects of Wear Out on Centrifugal Pumps

Very different strains can cause disturbances, wear out or also the total failure of a pump. For example these could be foreign elements in the volute, the impeller or in the pipeline. Other mistakes could be overload, wrong operation, which leads to cavitation or a faulty mechanical seal, which has the leakage as the consequence.

The transport of fluids with solid matters, which are moreover hard, causes a harmful abrasion on pump components. The reduction of the flow speed has a decreasing effect on wear out.

Delivery of special media, which are strongly alkaline, saline solution, acids or also seawater, cause more or minor corrosion effects. Also unplanned load modification without power adjustment have negative consequences.

1.1.1 Foreign Particles in the System

Solid particles like metal chips, deposits, grinding particle (sand, corundum etc.) but also components like screws, nuts or broken drills, which are very often delivered inside the fluids, could however destroy the pump. It is recommended, if solid matters with several millimeters of diameters are in the fluid and have to be pumped, a special free flow pump with an open impeller should be used (see figure 1).

There are already pumps available for processes where metal chips with a length of several millimeters must be pumped out. These pumps are equipped with a cutting device. The metal chips are already cut outside the volute to small pieces before entering into the pump. The small chopped chips could then be drawn in by the pump.

The solid particles do not lead as in the case of the closed impellers to blockage but are dragged along in the volute by the liquid to be transported out of the pump volute over the pressure filler neck again.

By operation with free flow pumps, the solid particles don't really enter the impeller, as shown in figure 2. The fluid with the solid components is drawn in by the impeller into the volute. By circulating under speed, the medium with the solid skids out again. [31]

Damages on Pumps and Systems. http://dx.doi.org/10.1016/B978-0-444-63366-8.00001-2
Copyright © 2014 Expert Verlag GmbH. Published by Elsevier B.V. All rights reserved.

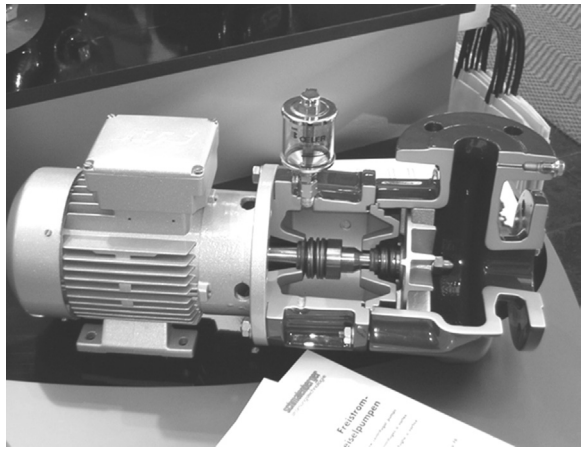


Figure 1 Free flow pump with confining chamber

It can be problematic at a solid matter quota of more than 10%, though. This, however, depends on the granulation or the size of the solid matters. Often, only an empirical ascertaining gives a solution.

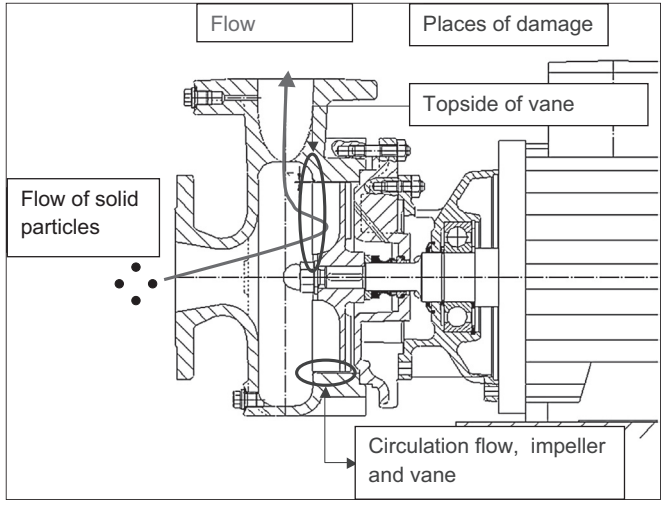


Figure 2 Flow in the pump volute

A longer-term operation with abrasive media leads however to wear out appearances, though.

Faulty spots arise, depending on the type of the solid matter, differently strong both on the vane top side of the impeller and on vane circulation side.

It is still the simplest opportunity, to replace the impeller after the damage. A complete exchange of the pump is often inevitable at greater damages to the volute.

It is recommended preventively at such applications, to protect the pump components by measures, such as hard overcoatings.

1.1.2 Overload

The wrong lay-out of the pump is a frequent failure cause. A higher solid matter quota than assumed, or another viscosity of the medium - oily instead of water-like - lead to overload.

Changes at the system, like pipe diameter, additional manifolds, fittings and valves, which do not draw an adjustment of the pump after itself, can also cause problems.

The maximum negative suction head has to be observed at self-priming pumps to avoid cavitation. For operation with frequency voltage system converters the permitted limits have to be taken into account. A missing non-return valve for a timed operation with short running cycles of the pump, leads also to damages on the pressure side.

The sudden change of the direction of rotation, leads to the destruction of the impeller seat, key groove or parallel key.

1.1.3 Pumping of Fluids with Solids

Solid matters are very often pumped out in fluids. In many media at given processes, considerable solid matter are contained in the fluids.

These are in cooling emulsions in tool machinery, grinding mud (sludge), in the area of sewages or in the production of textiles.

The following parameters have a very high influence on the temporal and the quantitative incidence of the wear:

- Rotation speed of the pumps [rpm]
- Solid matter quota in kg/l or kg/m^3 [%]
- Indicator for abrasivity
- Flow [m^3/h]
- Delivery pressure [bar]
- Hardness of the solid particles [HV]
- Temperature stability
- Layer thickness [in µm]
- Operating or Process temperature [°C]

The requirements on a pump which result from the media to be pumped can exemplarily be defined as follows:

Medium:	abrasive media, water, oil, emulsion, cold suds up to pH 10, solvent
Maximal temperature:	120 °C
Minimal temperature:	5 °C
Type of the solid matters:	Dirt, chips, cast and grinding particle, sand, quartz, glass abrasion

A definition as exact as possible, of medium and operating state helps to adapt the pump or the process accordingly.

1.1.4 Pumping of Fluids with Hard Solids

Since soft solid matters, are to be pumped quite good in the medium by free flow pumps, hard or very hard solid matters can cause problems, even cause a total breakdown.

Depending on the type and concentration of the solid matters in the medium to be pumped, it must be decided, which measure the best solution provides. There is no ideal solution. Depending on application {employment} different measures like rubber coating, surface remuneration, inlets of ceramic, plastic overcoatings or hard cast can offer the solution.

While rough particles are leading to signs of wear out mainly to impeller and volute, do grinding particles, sand or glass abrasion cause damages to bearings, shafts and mechanical seals.

Pipe diameters and flow speed have a very big influence on the degree of the damage and the length of the service life of the pump. The bigger the pipe diameter and the less the flow speed (velocity), the less is the damage and the higher is the service life.

1.1.5 Faulty Running and Operating

An operation which does not match the operating point necessary for the application, can have very different reasons. A wrong lay out can considerably lead to the running of the pump in the extreme case outside the operating point. Harmful vibrations with damage of bearings as a consequence, or overload and destruction of the motor can be the result. If agressive media are used, the wrong material can cause corrosion and leakages. If submersible pumps in the “slurping operation” are pumping out of a container, too much air can lead to dry run and failure of the mechanical seal.

A wrong piping can increase the decrease in pressure unnecessarily and also cause overload. If the solid matter quota is too high, the pump can be blocked, failure in pump power output or a total fail. If it comes to defects with the pump, then it is very often not a problem with the pump, but a system error.

1.2 Wear Out through Abrasion

An abrasive wear out is defined as a kind of micro shaving at which it comes to the abrasion of material on components. The hard, abrasive material in the pumping medium is harder than the material of the pump components.

Abrasive media are in lot of liquids which are delivered through pumps. Depending on solid matter the service life of the pumps gets considerably reduced, partial by harms to impellers and volutes, sometimes within only a few weeks. Under the aspects of Total Cost of Ownership (TCO) and Life Cycle Costs (LCC), this means a drastic rise of the operating costs.

In the operation of tool machines, the centrifugal pumps are very frequently used for the transportation of cooling emulsion loaded with solids, abrasive liquids. Metal shaving, grinding dust and corundum rub at volutes and impeller so strongly, that the pump fails after a short period of time.

Examples from the Practice

In the textile chemistry on textile cleaning abrasive solid matters are found in the sewage, for example at the refining of jeans.

In the civil engineering for example the abrasive lubricant "bentonite" is used. Bentonite is a rock mixture of different clay materials (among others: quartz, mica, feldspar etc.) and is applied for sealing up buildings and in the field of dyke building, and as lubricant for tunneling construction. The abrasive effect on pumping out of liquids with bentonite pollutions is considerable (see figure 3).

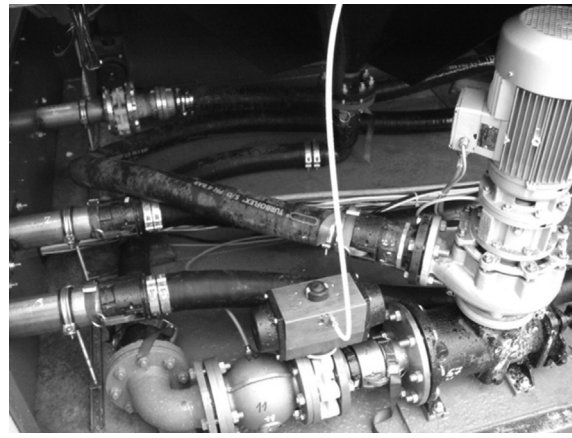


Figure 3 Centrifugal pump installed to a system for pumping bentonite

In the field of solar cell manufacturing (photovoltaics), submersible pumps are used for extracting the grinding muds (Slurry) when sawing silicon wafers. These grinding sludges consist of a mixture of glycol and silicon carbide as abrasive compounds (see figure 4). The wafers (thin silicon wafers) are sawed with a steel wire from the casted silicon blocs. The Operation is a permanent circulation of the abrasive compound "silicon-carbide/glycol" in the 24 h, when pumping the medium. The abrasives quota amounts to approx. 20 weight %. The permanent circulation is necessary, otherwise the abrasive compound gets hard.

Continued

Examples from the Practice—cont'd

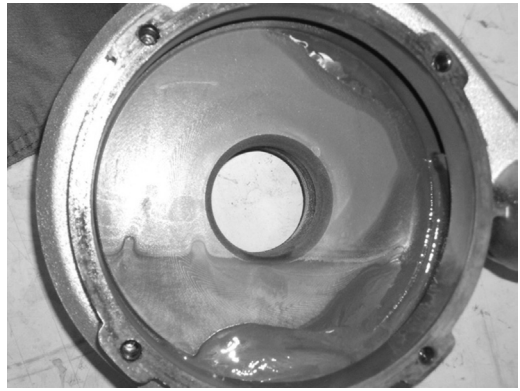


Figure 4 Spiral volute after test with grinding muds "Slurry"

At all these applications the service life of the pumps is reduced by this abrasive wear out considerably.

1.2.1 Impeller

The material erosion on the impeller takes place at very different spots. Flow simulations pointed out very clearly, that the damages are strongly related to the velocity of the fluid (see figure 5). The greatest abrasion takes place on the impeller surface, where the fluid has the highest speed. Furthermore, an increased erosion appears on sites of a turbulent flow of the medium (see figure 6).

Figure 5 Damaged impeller by abrasion

Should abrasive media be transported, it is recommended to use pumps with an open impeller. Using free flow pumps for pumping solid matters with a particle size of 3-5 mm, with a maximum solid matter quota of 5-8 %, it is possible to prevent wear out on impeller and volute of the pump. At higher solid matter quota, this can lead to blockage or get the impeller vanes grinded down completely.

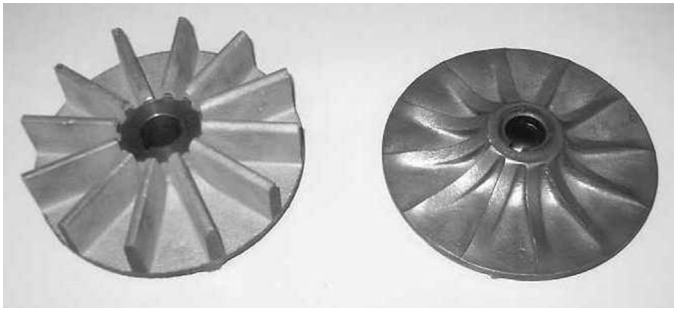


Figure 6 Impeller before and after the damage – material erosion by abrasion

1.2.2 Volute

The most material erosion takes place on edges inside the volute. For example: at the emptying hole or the drill on the wear out plate. In addition, even a similar damage takes place inside the volute with fluids containing grinding particles.

A phenomenon which can appear is an abrasive surface, arising out of the flow, according to the principle of flow optimized shark skin as shown in figure 7. The assumption that a surface as slippery as possible has the lowest resistance is wrong. By the lengthways grooves on the shack the crossways flow is lowered and therefore reduces the friction. This principle is already applied successfully in the aircraft industry.

Figure 7 "Shark skin surface" in the pump volute

If the wear out takes place so evenly, the wall thickness reduced can absolutely withstand, so that the service life of the pump can be acceptable. Concerning the flow effect of this surface "shark skin", it is even a loss minimization since this surface is actually ideal. If the wall thickness is appropriately high enough, this type of wear can shorten the life cycle of the pump only insignificantly.

1.2.3 Bearings

An overstress of the bearings occurs, if the radial force is too high. If the pump is driven with a considerably higher discharge than scheduled, it comes to the flexing of the shaft with a following damage done to the bearing. Also by strongly abrasive media the bearings of pump and motor are hurt as documented in following illustrations as shown in figure 8. Grinding mud seems primarily very strong to edges and splits.

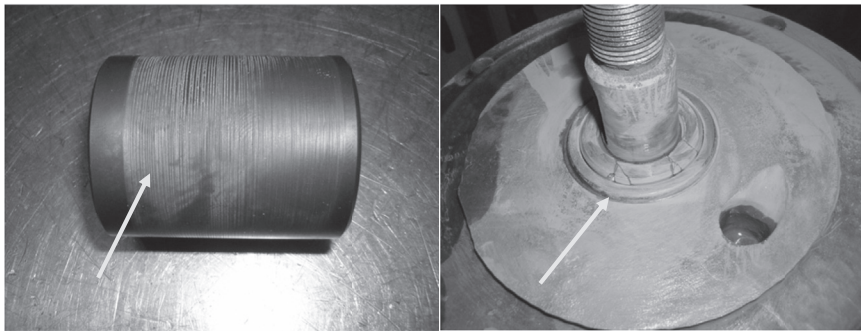


Figure 8 and 9 Damaging of the throttling bush - consequence: damage to the motor-bearing

Abrasive wear out also leads to antifriction bearings primarily into connection with corrosion to destruction. As a result it comes to amplified mixed friction and material erosion. The noise level increases continuously, the wear out further gains in cage simultaneously and rolling body increases up to the end, until the final destruction of the bearing as shown in figure 9.

Possible protective measures can be: protection ring for the motor-bearing, erection of a wear out sensor with supervisory system or a motor circuit breaker. A higher-quality motor as applied in explosion protection area could also be useful.

1.2.4 Piping

With sufficiently big pipe diameters, both flow losses and damages by abrasion can be reduced. If the pipe diameters are chosen too narrow for cost reasons, there is no stabilized laminar flow, but a turbulent flow with irregular crossways flows in the pipe. If solid particles are in the flowing medium, these have an effect to the inside wall of the pipe as in the case of a process of grinding. The strongest material erosion takes place on pipe narrowings, manifolds or also T-fittings. The solid matter particles bump against the appropriate places with increased force and wash or rebore the pipe more or less until finally the pipe

wall breaks through as shown in figures 10, 11 and 12. This can happen very fast at thin-wall pipes. Regarding protective measures, it will be dealt on in chapter 4.

Altogether, with small tube diameters investment costs could be reduced, but energy expenses cannot be saved.

The increased pipe frictional resistance in pipe wit smaller diameters compared to pipes with a wider diameter, still strengthens by a high roughness in the tube, brings about a rise of the decrease in pressure. This means more pumping capacity and more energy consumption is needed. To the gentle operation of a system, for the reduction of wear out and also for the minimization of the noise level, one measure definitely is the enlargement of the pipe diameters.

Figure 10 Frayed tube bends

Figure 11 and 12 Really big holes in the tubes (abrasion)

On abrasive media, it has to be paid special attention therefore on the strength and resistance features. Relevant harms have to be expected also on fittings like valves, slides, measuring sensors if the materials are not sophisticated enough (see figure 13 and 14).

Figure 13 and 14 Cross-section of a tube bend: the wall thickness is reduced by wear drastically

1.2.5 Abrasion and Corrosion

If solid matter particles are transported in a corrosive medium, it comes to an overlapping from abrasion and corrosion. Usually, the abrasion rate is not easy to forecast. This is, however, very high on too high flow velocity and turbulent flow.

The service life of a pump can vary significantly, depending on grinding medium at grinding machines, for example. Depending on composition, granulation of the grinding sand and flow speed, the service life can be increased by 20-40 % by reduction of the flow.

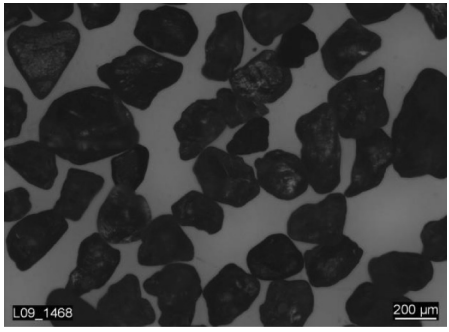


Figure 15 Grinding grains of sand, new

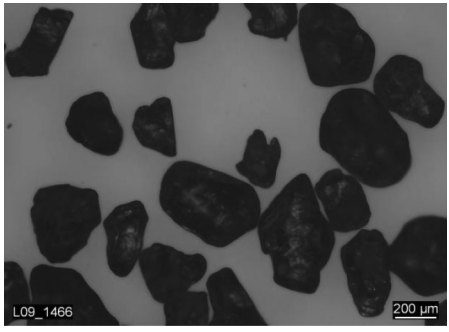


Figure 16 Center punch, sharpened

The figures 15 and 16 show the center punches of the grinding sand used at grinding processes. The left figure (15) shows the sand newly, in the right figure (16) the edges and corners of the grains of sand are already "rounded off" after approx. 100 hours bows. Depending on how often the grinding sand is exchanged in the process, the service life of the pump can therefore varying significantly.

Figure 17 Wear out by abrasion and corrosion at the impeller

Once deepening in the surface have arisen due to material erosion, the further destruction can take place very fast. Due to deepening, a turbulent flow arises which still accelerates the material erosion.

From the surface, damaged by corrosion, the material pieces breaks out of a superimposed abrasion and are washed away by the medium. By renewed corrosion and following abrasion, the material is washed out until the break or formation of holes as shown in figure 17.

The amount of the pH-indicator of the fluid medium is very decisive for the damages on a superimposed corrosion. If the pH is very low (< 5), the passive layer on the surface is destroyed and it comes to pitting.

Intercrystalline corrosion can arise when acids are pumped. The acids destroy the metal structure of the material and let the material corrod from inside out.

A fluid medium is uncritical with a pH of 6.5 - 7.8. The so-called Pourbaix diagrams which paraphrases a fundamental permanency in different pH areas also give a statement about this.

The material abrasion on critical sections in the spiral volute, such as at the mating surface spiral volute/lid, leads to leakage as shown in figure 18 and 19. In principle can be said, that the risk of the corrosion at high-grade steel/-cast also on salt-/ seawater increases as follows:

The high-grade steels are conditionally noncorrodible [14]:

Ceramic Inserts

By very hard solid matters, remedial action can be taken by installing ceramic inserts on the very stressed places.

Monitoring by Means of Sensor

Monitoring by means of an abrasion sensor offers the opportunity of the wear out to be indicated by a signal.

4.3.1 Wear Out Reducing Inserts

To extend the life time of the pump cases, a quite simple and economical measure offers its services with a wear plate in the pump case. Since the pump case does not have to be taken off with the piping in the claim, for the exchange of the wear out plate, the effort for replacement is relative comprehensible. Price comparison with a new pump case is not necessary.

Figure 63 Wear plate in the pump case (before damage)

Figure 64 Abrasion at the screw bores (after damage)

By comparison of the two photos (see gure 63 and gure 64 [24]), it is recogniz able that the abrasive material removal starts at the edges of the screw bores. Before the complete, quite thick wear-out plate is worn out, the screw heads fall down most likely. If the delivery uid contains very hard wear particles, wear protection - made of ceramics - for system components and pipes is recommended (see gure 65 [11]).

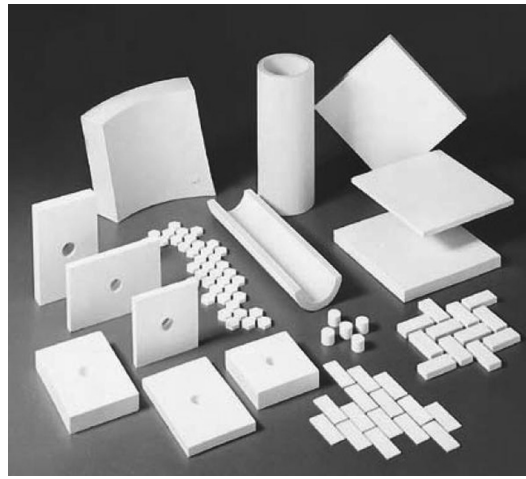


Figure 65 Different ceramic Inlets [11]

Such inlets are available with very different wall thicknesses, sizes and geometries. For large pipes they can be tted in very easily. By smaller pipe diameters, limits are set out on wall thicknesses. However, special designs are usually practicable.

4.3.2 Monitoring by Means of Sensors

The material abrasion on the impeller can be detected by a decreasing power output of the pump, while the abrasion on the pump case is noticed only at the leakage of the delivery uid. This is a critical factor on pumps for dry installation, since the leaking uid can then run out to the surrounding area. To recognize this wear-out earlier and be able to start appropriate maintenance measures, it is very suitable to use a system with wear-out sensor (see gure 66, 67 and 68 [24]).

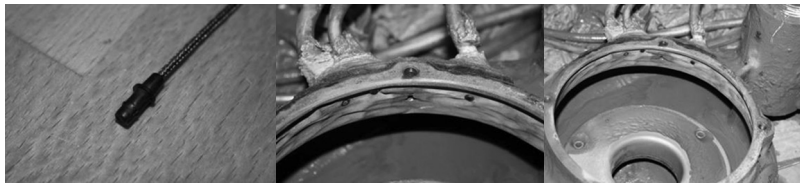
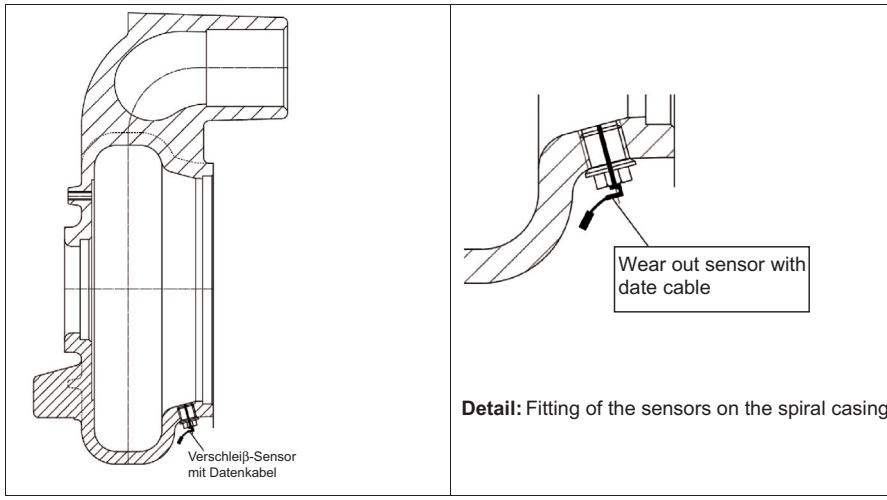


Figure 66-68 Installation situation of the sensor

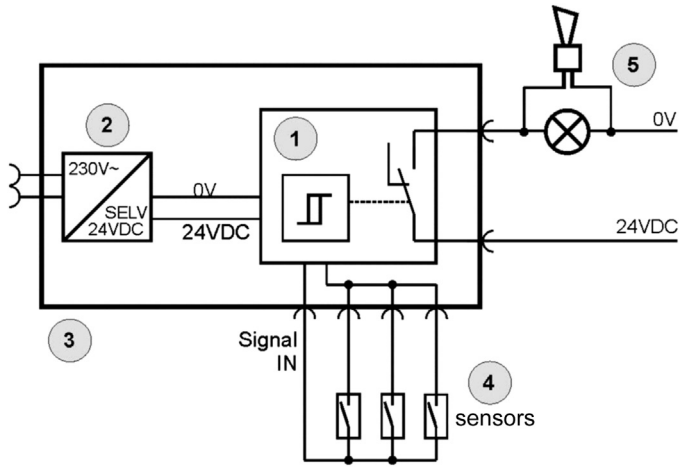


Graphic 4 Abrasion sensor in the pump spiral casing (volute)

The wall thickness of pump case components should be monitored with the help of sensors. The wall thickness should be monitored on such spots where material removal by the abrasive uid is very huge. Due to material removal, arises the risk of leakage through the leak on spiral casing on the surrounding. Here a system with a wear sensor is useable

4.3.2.1 Functional Description

The wear sensor is installed at case areas which are affected particularly by the abra sion. At this sensor principle, the conductivity of the uid is utilized. The sensor, whose core consists of conductive material has a cylindrical form which is surrounded



Graphic 5 Connection circuit diagram of the abrasion sensor

by an insulating coating of synthetic material. The sensor is stuck in into a blind hole, leak-proofed (see graphic 4 [24]). By the sensors, installed in different depths the material abrasion can be observed and measured.

The sensor is connected to a 24 volt voltage source (DC) (see graphic 5 [24]). The ground line is fastened to the case and connected to the analysis unit. This unit is a threshold switch, whose shift point is adjusted to a maximum sensitivity of 1 V. The abrasive uid excavates the protective layer on contact with the sensor. The electrical contact to the case, then is drawn by the uid. If the switching voltage is exceeded, a are and acoustics signal will be activated over a potential-free switch.

If such a wear-out sensor is positioned very well, foresighted measures can be taken. Before the wear-out leads to damage, the spiral casing can be replaced in the context of the servicing.

4.3.3 Rubber Coatings

Rubber coatings, for example from EPDMs, are usable by limited condition on abra sive delivery uids (see gure 69 [24]).

EPDM (ethylene propylene diene monomer) as a type of synthetic rubber, is an elastomer with a wide range of applications.

Since the rubber coating is softer than the metal particle, the rubber, as an elastic material is resilient, when the particles are colliding. The particles bounce off and are further transported with the delivery medium.

Figure 69 Rubber coating of spiral casing and back plate

Before the rubber coating is applicated, the surface must be cleaned very well, so that the adhesive strength on the metal gets rmly enough. A primer (adhesive layer) must possibly be used. The thickness of the rubber coating should be max. 4 mm. The solid matter quota in the uid should not exceed 15%.

It is a disadvantage, that the pump components must be strongly surface nished, before the rubber coating, so that the layer thickness of the rubber coating can be compensated.

Depending on strain, however, the wear-out will also not fail to appear sometimes. After certain time, nevertheless small rubber particles are excavated and small cracks also might arise. The service life of a pump can absolutely be doubled, depending on stress also more After first damages, however, the rubber coating might be worn out and excavated partly.

4.3.4 Wear Resisting Materials of Cast Iron

By abrasive, corrosive strain, white cast iron is very often used. This material also indicated as chilled casting or hard cast is very much wear-out resistant. The exceptional feature of this material includes that the carbon content is chemically bonded as carbide. The fracture surface is white or silverly, unlike the gray of the cast iron. There are different kinds of hard cast, depending on alloying quotas and alloying degree. Depending on the structure by unalloyed or low alloyed sorts, chromium carbide, molybdenum carbide, niobium carbide or vanadium carbide arise. The hardness of the carbides reaches from 800 Vickers (HV) by cementite, 1 600 HV by chrome carbide up to 2 800 HV by vanadium carbide (see table 13).

Table 13 Hardness Values of the Cast Iron Materials in Vickers (HV)

Material	Hardness in Vickers [HV]
Cementite	800 HV
Chrome carbide	1 600 HV
Vanadium carbide	2 800 HV
Cast iron	210 HV

A hard cast, where nickel and chrome as alloying components are contained proportionally 2:1, is known under the trade name “Ni hard” (e.g. Ni-hard 1 or Ni-hard 4). The qualities can be varied by the change of the carbon content [38]. Although, the chrome {chromium} content is partly very high (> 20%), the hard cast it not very corrosion-resistant The reason is, that the main quota of the chrome is bound in the carbides and the content of other alloying elements, such as nickel or molybdenum, is not sufficiently high. Nonetheless the corrosion resistance is strongly dependent on the chemical composition of the delivery fluid.

Such materials can be applied well by strongly abrasive media, such as sand-/ water mixtures. However, since the alloying costs are relatively high, this application will be suitable mainly for very special solutions. In addition, the components made from hard cast require special cast tools.

A post-machining (trimming, threading) of the castings is only possible with special tools.

For example, a power matching of the pump by changing the impeller diameter by trimming is complicated.

4.4 Surface Reimbursement

This is not an upgrading by a galvanic procedure, but a speci c “hardness increase” of the surface layer which causes an increase of the strength against abrasion. As already described in chapter 4.2.1, the selection of the wear protective layer is based on three steps of the systematic failure analysis: Damage description, fact- nding and damage hypothesis. After an analysis and exact knowledge of the damage image or the wear-out appearance it makes sense to x the requirements on the layer sub stratum system. On one hand the tribological requirements as well as constructive and manufacturing-related requirements have to be xed to conclude nally the material requirements. A selection of suitable wear-out protective layers can then be carried out.

4.4.1 Hard Layers

As already described in chapter 4.2.1, the choice of a coating system is not only the choice of the layer itself, but it means the choice of a suitable combination of base material, coating, layer thicknesses and material transitions (see Graphic 6 [31]). The hard layers belong to the reaction layers.

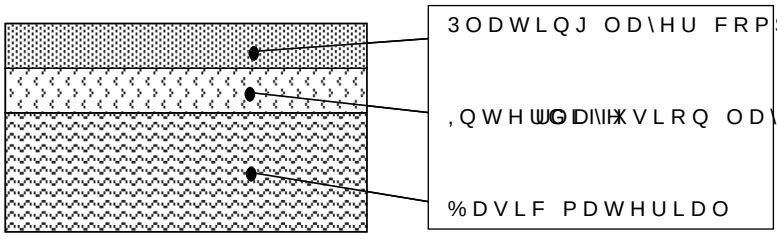
The reaction layers arise from in uence to the surface layer e.g. through heat, diffusion or implantation of alloying elements.

“Soft” materials can be hardened by a special surface termination in the surface layer. Consequently through their greater resistance to abrasive media, the service life of the pump can be increased considerably.

The adhesion of the layer on the cast iron surface is a problem by different sorts of coating processes. By an ampli ed sandblasting or glass bead blasting, the layer must be prepared for the coating process. By thin layers an additional smoothing still must be carried out to be able to obtain a satisfactory result.

The laser surface cladding is suited very well under the “high-build” ones, since the thickness of the layer de nitely can be > 1 mm.

By the nitriding and nitrocarburisation the friction coef cient and the adhesion inclination is reduced, on the other hand increases the abrasion resistance and the strength against fatigue by change deformations [36].



Graphic 6 Substratum layer structure [31]

4.4.1.1 Nitro-Carburisation

The nitro-carburisation implies a process of nitriding (gas or saline bath) which means that from the nitriding material, both nitrogen and carbon are diffusing into the surface of the component.

The item is exposed to a carbonous and nitrogenous surroundings atmosphere by a temperature of 480 to 590° C. By the nitrogen and the carbon, a change of the chemi cal composition and the structure takes place in the surface layer.

4.4.1.2 Plasma-Nitriding

The process of nitriding takes place in the plasma (electrically, conductive gas) in a vacuum stove at 350 to 600° C. The nitrogen from the nitriding material diffuses into the surface and causes a change of the chemical composition and the structure in the surface layer (see Figure 70 [24]). In this context, a very low deformation and an only insigni cant size alteration arises through this process (see Figure 71 [24]).

Therefore, this process is for thin-wall components more suitable than the nitro-carburisation.

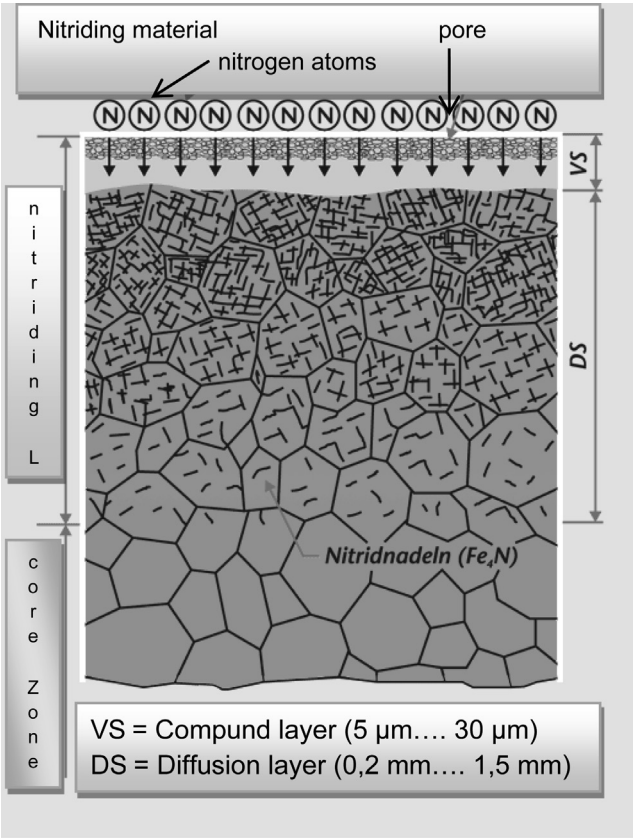


Figure 70 Nitriding layer and core zone after the plasma-nitriding process [24]

Figure 71 Impeller with nitriding layer after the plasma-nitriding process

4.4.1.3 Laser Surface Cladding

During the laser surface cladding, material is locally and precisely applied on to the surface.

The material can be adapted exactly to the load case, with respect to hardness and the mechanical properties (see gure 72 [24]). This layer has a hardness of 900 Vick ers (HV), thereby it has a very high stability and causes by the high layer thickness of 1 mm a rise of the service life. An adjustment of geometry is necessary, though, since the hydraulics is changed (size alteration) by the laser surface cladding.

Due to the relatively thick layer and the special mode of the manufacturing method, wear-out plate and impeller can be coated - according to the requirements of the appli cations - up to max. 1000 µm (1 mm) layer thickness.

The low, but concentrated heat input guarantees very low deformations. The principle of laser surface cladding or plating consists in building up powdered material by welding on a component, so that tightly adhesive and increased marks arise (raised welding bead) (see gure 73 [24]).

Therefore, the material of the workpiece will be partly fused, with the help of a focussed laser beam in the focal spot. At the same time, additional material is brought into the molten puddle and also melted on. After the solidi cation, the additional mate rial is tightly sticking on the workpiece. This process is happening fast and continuously (see gure 74 [24]).

By the combination of individual coating tracks, at and multilayer coatings can be realized, such as they are needed for the repairs and the wear-out protection (see gure 75 [24]).

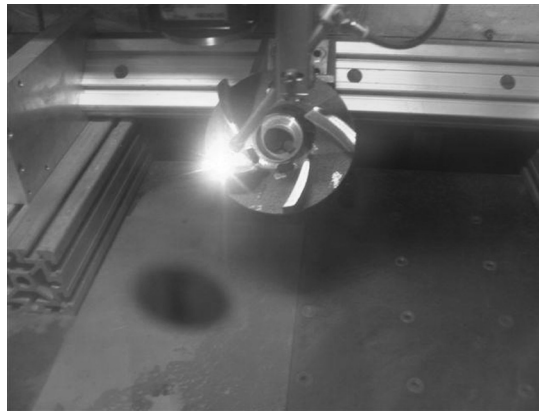


Figure 72 Laser surface cladding on the impeller

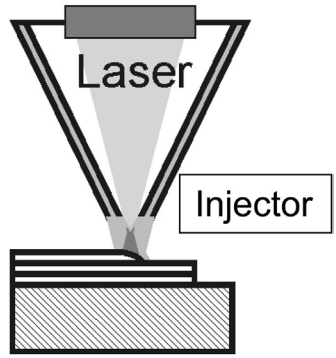


Figure 73 Principle of process

Figure 74 Impeller with laser surface cladded vanes

Layer thickness: 100µm
Hardness: 900 HV

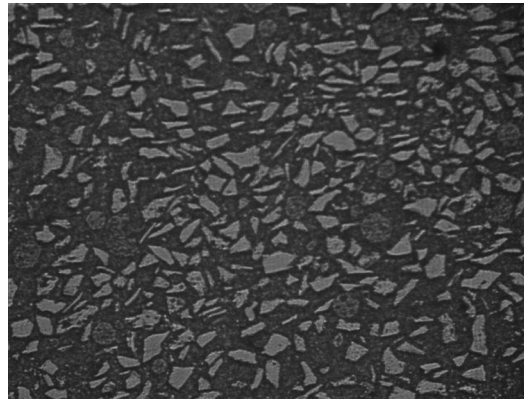


Figure 75 Structure micrograph of a laser surface cladding layer

4.4.1.4 Carbon Layers

Carbon layer ta-C (tetrahedral amorphous carbon):

Due to the relatively thin layer thickness, the substratum must be preconditioned before the coating. In addition to the sandblasting or glass bead radiation, the compo nent surfaces should be smoothed by grinding. The carbon layer has a hardness of 4 500 Vickers (HV). This procedure is suitable for the plating of the impeller.

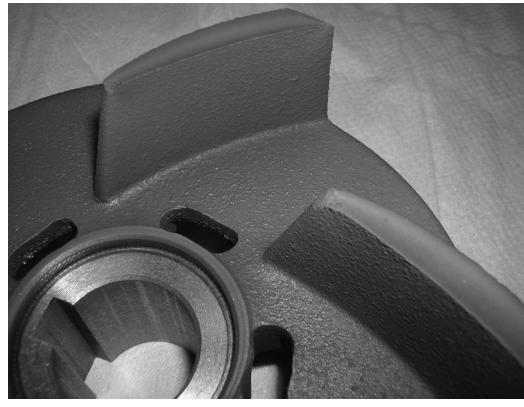


Figure 76 Impeller with amorphous carbon layer

The process:Laser controlled vacuum arc plating (laser arco)

The laser Arc plating principle combines the advantages of the processes VAD (Vac uum Arc Deposition) and PLD (Pulsed Laser Deposition). By the use of an economical

pulse laser, a temporal and local control of the arc discharge gets possible (see Figure 76 [24]). With the help of a laser pulse, an arc with a very strong electrical current, with a peak current of about 1.8 kA (kilo Ampere) is sparked, whereby the duration is limited to 130 micro-seconds (µs).

The amorphous carbon layer is vapoured in the PVD process by graphite vaporizing.

The laser Arc module can be docked at every customary plating system (see structure micrograph Figure 77 [24]).

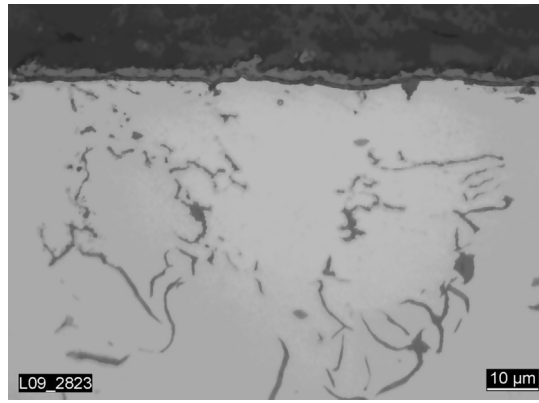


Figure 77 Structure micrograph of the ta-C-layer

4.4.1.5 Diamond Similar Layers

Duplex Layer

The very hard silicon carbide (SiC) is contained in this layer, whereby a layer hardness of 2 600 HV (Vickers) is achieved.

The layer thickness can be applied up to 100 µm. This layer is suitable for spiral casings and impeller (see Figure 78 [24]).

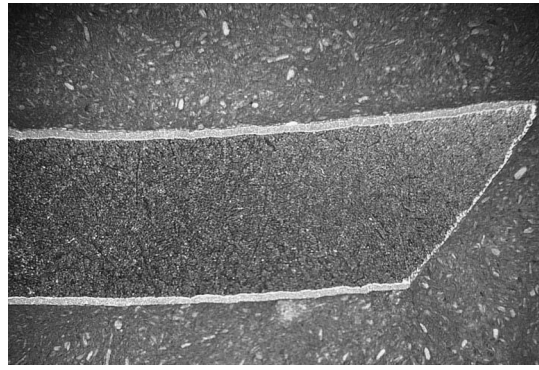


Figure 78 Micrograph of the duplex layer

Characteristics of the layer:

- Diamond particle sizes 1 - 45 µm
- Typical particle sizes: 1-3 / 8-12 / 20-30 µm
- Particle size: 1-3 µm
- Enclave volume: 25 - 40 %
- Layer thickness: up to 100 µm

Plating process:

The rough diamond particles are fixed in the first plating step on the surface. The free space between the rough diamond particles is filled out in the second plating step with another dispersion plating up to the desired embedding quotation (see figure 79 "surface structure" [24]). This second dispersion plating contains considerably finer diamond particles. By the duplex plating, the wear-out resistance of the chemically nickel - matrix REM increases considerably.

Duplex layer:

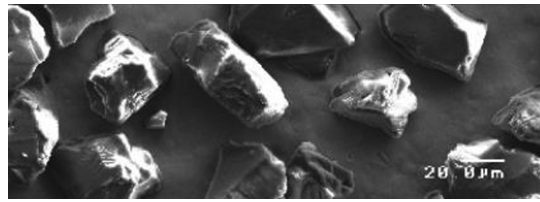


Figure 79 Surface structure chemical-nickel-diamond (particle size 40 µm)

4.4.1.6 Summarizing and Evaluation of the Plating Processes

Different plating processes are suitable for the protection against abrasion (see table 14). Depending on application and solid matter (chips, grinding dust, sand, very hard solid matters), it must be decided about the process to be used and the layer thickness. A selective plating, especially by laser surface cladding, is very well possible, depending on application.

Table 14 Hardness and E-modulus (Elastic Modulus) after the Plating

Material	E-Modulus [N/mm^2]	Hardness [HV]
Cast iron, without layer	100 000	210
Cast iron + nitrocarburisation	110 000	600 – 660
Cast iron + plasma-nitriding	110 000	1160 – 1200
Cast iron + laser surface cladding	210 000	900
Cast iron + ta-C (carbon layer), (Diamor)	300 000	4 500
Cast iron + chemical-nickel-dispersion plating with diamond particles (duplex)	145 000	2 600

The production procedures are compared in the following evaluation matrix to give some basic information for the decision on the layer selections (see Table 15).

Table 15 Production Processes

Layer:	ta-C	Duplex	Laser Surface Cladding
Layer thickness	10 µm	50 µm	1000µm
Production processes	Vacuum arc plating (laser-arco) with amorphous carbon Electrical power input: > 20 KW	Fixing of the diamond particles on the surface and replenishment of the free space with dispersion plating Electrical power input: > 30 KW	Building up with weld of powder-shaped material. Electrical power input: < 10 KW
Process time for one impeller	4-5 h	2 h	5 minutes
Process-temperature	< 180° C	90° C	1 300° C
Tempering follows		350° C	

In the context of the predictive maintenance, a load pro le can be created for pumps, using the wear-out data and the details on ow speed and operation hours. A ow simu lation gives information about the strongly stressed sectors inside the pump.

Especially for special applications, an appraisal can then be made, about the service life of the pump to be expected.

An increase of the service life justi es therefore this additional costs arising for the plat ing, because through this the costs for the loss of production can be reduced enormously.

4.5 Special Designs

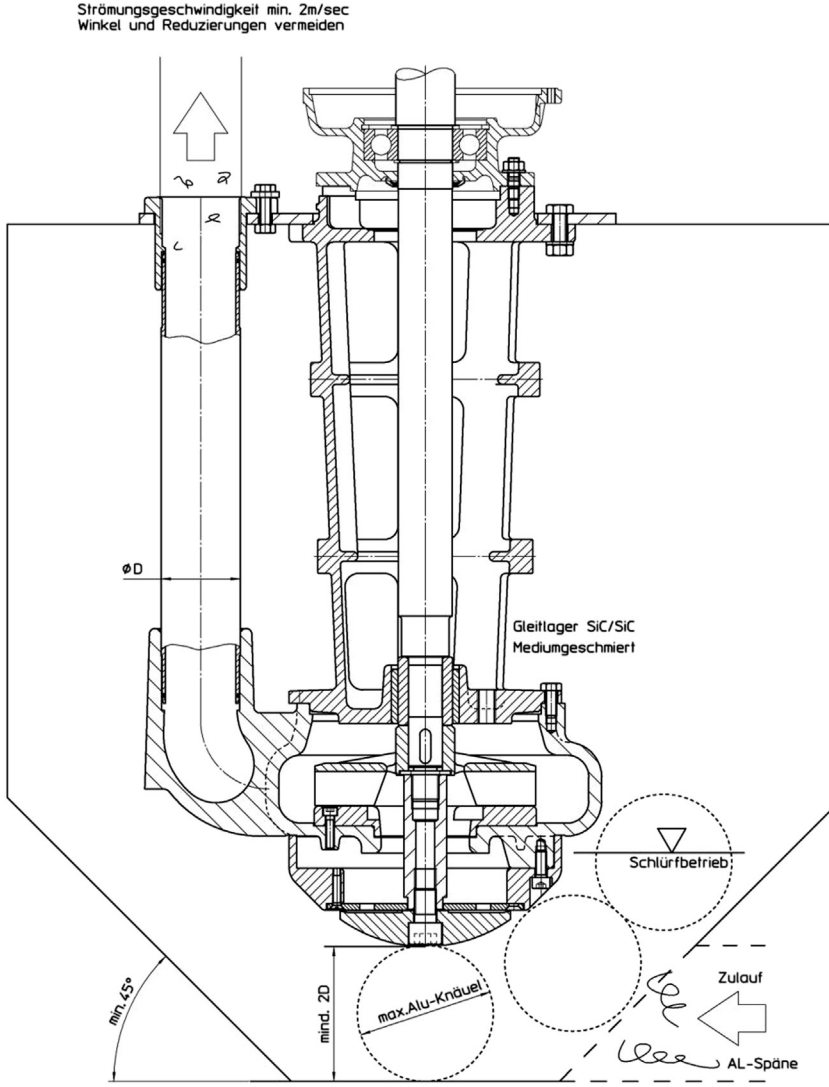
To minimize the damages at particularly wear-out af icted processes and to increase the service life of the pumps to an acceptable dimension, different special designs are practicable in addition to the platings.

4.5.1 Pump with Cutting Unit

Among other things, pumps are also used in the eld of metal cutting machine tools for delivering of refrigerant uids, polluted with metal chips. The metal chips very often forms balls which hinder the delivery of the refrigerant uid reliably. For saving expenses, steel wool shredders (steel wool breakers) or lifting systems, which are expensive and effortful are frequently renounced. For this reason it makes sense to combine pumps with cutting tools. Therefore, a pre-shredder gets preconnected on the pump shaft, mounted in front of the real impeller.

By different pumps on the market, pumps with cutting edge and pre-shredders are arranged inside the pump case. The pre-shredder is surrounded by the suction pipe of the pump so that the crushing of the steel wool balls to small pieces is happening in the pump case. Nonetheless there is a risk of the blockage, if the scouring with steel wool balls are too big or the chips are not cut small enough.

Other systems consist of a pump and a separate steel wool breaker (crusher). These systems are more complicated, require more space and increase the invest ment costs.



Graphic 7 Installation of the pump with cutting unit in a container

Another version of a single-stage centrifugal pump in a compact bloc construction is a type, equipped with a cutting unit, pre-built in front of the impeller (see Graphic 7 [24]). The cutting unit is xed on the extended pump shaft. Here, the cutting unit sits directly in front of the pump case, but outside the casing, however. As soon as the uid is drawn in with the chips, the chips can be crushed by the cutting edge, before they enter the pump casing. The cutting edge crushes the steel wool balls and cuts the chips (see gure 80 and 81 [24]). The pump can thus work blockage freely through this and the good sucking characteristics remain unchanged (see gure 82 and 83 [24]).

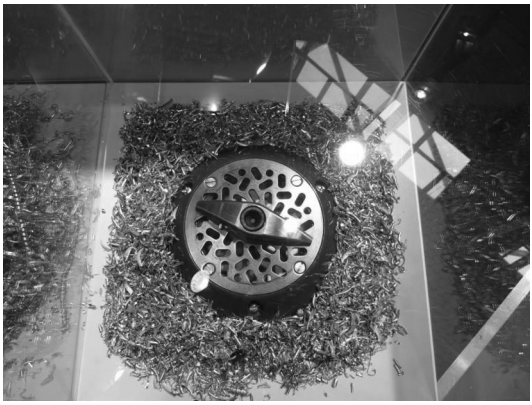


Figure 80 Cutting unit with cutting plate

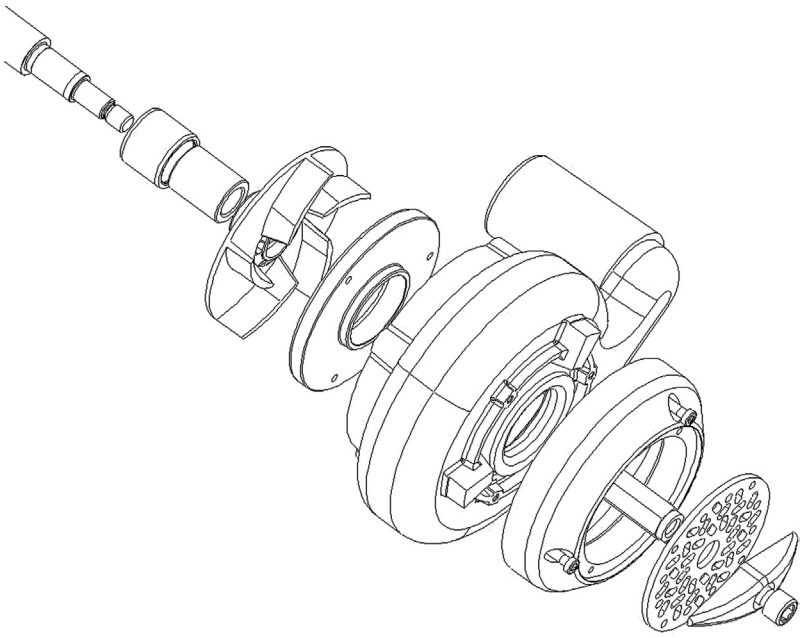


Figure 81 Pump with cutting unit

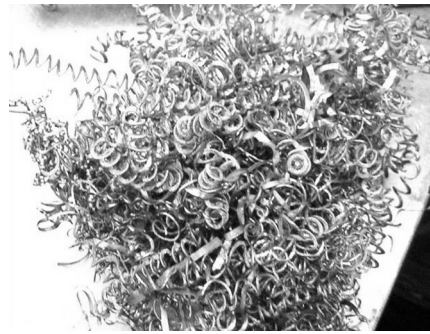


Figure 82 metal chips before crushing

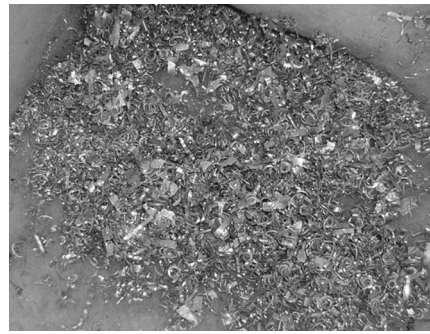


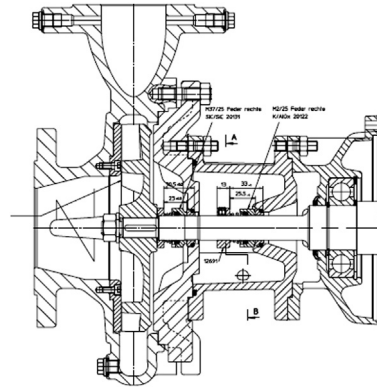
Figure 83 metal chips after crushing

Cutting plate and the edges of the cutting unit are hardened and thereby very resis tant to wear-out.

The holes in the cutting plate are shaped as long holes and designed in a way that the pump inside is protected from too large parts. Thus items, such as broken drills, cannot reach the pump and not damage the impeller.

4.5.2 Pump with Inducer

By different applications, pumps work in some processes with low negative suction heads. This can be the case by processes with negative pressure or if delivery uids with a low boiling-point have to be pumped. The required NHSH value has then a borderline value, so that the risk of cavitation is very high.



Graphic 8 Pump with Inducer [24]

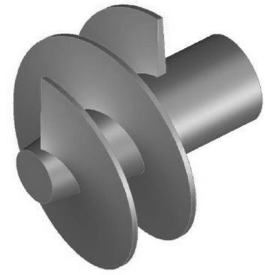


Figure 84 Inducer

To minimize this risk and possibly exclude damages, an inducer-impeller can be assembled on the pump shaft, directly in front of the pump impeller (see Graphic 8 [24]).

This “Header impeller” with a helical geometry increases the pressure at the impel ler inlet as it were a “pre-pump”. It minimizes the risk of cavitation and prevents the resulting damages from it (see Figure 84 [24]). In addition, through the inducer, noise and energy losses are minimized.

5 Mobile and Stationary Damage Monitoring

Stationary systems for condition or damage monitoring are generally more complicated and more expensive than mobile systems. Criteria for the selection are: demanded frequency of the measuring signals, necessity of a trend analysis, required precision of the measurements, exposure to be expected and the expected risk of damage. Last not least, a costs-benefit analysis is decisive.

5.1 Mobile Damage Monitoring

If a pump is newly installed, it makes sense to monitor this unit for a given time. Important knowledge arises about this, whether the lay-out of the pump had been correctly done (type) and whether all technical requirements are fulfilled. The analysis of the pump readings and the noise level deliver important knowledge about the process flow and operating condition of the pump. It can also be found out whether the pump runs in the scheduled operating point.

If a new pump with different specification shall replace another pump, can be investigated by the monitoring whether the pump fulfills the full function of the old pump and whether the performance of the pump is sufficient. Thus the risk of a damage occuring later, can be minimized in an early stage. Provided that the results of the monitoring are satisfactory and the regular processes do not lead to any disruptive incident, the pump monitoring system can be dismantled again and installed on another pump.

The parameters, described in chapter 2, like pressure, temperature, speed, etc. can be measured with mobile gauges. Mobile compact devices are also available for measuring vibrations, condition of the ball bearings and for cavitation, even for evaluation and documentation. Much effort and costs can be economized by such mobile gauges since the mobile, short-time monitoring is sufficient for less critical systems and no stationary measuring system is necessary.

5.2 Stationary Condition Monitoring

Monitoring with a stationary system makes then sense, if endangering delivery media are in use or if a disturbed process flow of the pump system can cause very big damage. Hazardous materials or fluids can become risky by too high pressures or temperatures or lead to damages by leakage or overflowing of the delivery medium from the container. Often, the subsequent costs exceed even the costs for the real damage.

Critical processes, which require a very continuous delivery flow over a longer time period - at least in the 24 hour operation - can hardly resist without a stationary

Damages on Pumps and Systems. http://dx.doi.org/10.1016/B978-0-444-63366-8.00005-X
Copyright © 2014 Expert Verlag GmbH. Published by Elsevier B.V. All rights reserved.

condition monitoring system. Strong fluctuations of the system parameters can be commanded by monitoring and controlling. Particularly in explosive areas, a monitoring system is very essential. It has to be distinguished between dust explosion and gas explosion. The pump- and plant components must comply with the valid EU instructions for the respective, explosive atmosphere. Here a so-called ATEX admittance is required. By very complex processes, in addition, the opportunity of the teleservice by a special company is obvious.

5.2.1 Structure of Stationary Condition Monitoring

For the exact measurement recording, it has to be paid attention on a proper installation of the individual components and the equipment being part of the system. Apart from the pump accounts also sensors, data lines, measuring box, PC and network.

Measuring errors appearing by wrong installation can have devastating consequences. Also applied software must be checked regularly.

For setting up of a monitoring concept, measurements must be carried through to investigate the limiting value. To this, specifically measurements at disturbances are carried out. The sequence of operations forms itself as follows:

- Measuring of the disturbances
- Storing the readings
- Analysis of the readings
- Specification of the limiting values
- Documentation in spreadsheet systems

The measurements in the process then require:

- Measuring of the process parameters
- Analysis of the readings
- Comparison of the values with the limiting values
- Identification of the limiting value exceedings
- Evaluation of the limiting value exceedings

If disturbances appear, there are different possibilities to reprocess the disturbing reports:

- Display on the screen with error message
- Display on the screen with error message and transmission to a primary terminal
- Display on the screen with error message and immediately reaction e.g. “pump stop”.

The disturbing report can also be defined and transferred as an alarm report such as:

- Production stop
- Alarm transfer in the company’s network
- Alarm by e-mail to offices outside
- Alarm by e-mail to servicing company

If an automated condition monitoring system shall be implemented, a regular, also automated analysis of the readings takes place. This analysis means that the

identification of a disturbance through this results, that a measurement comparison with the deposited limiting values is carried out.

The following signal on the recognized disturbance according to a limiting value exceeding can be reprocessed in a very different way:

- Display at the monitor
- Ring tone
- Flashing signal lamp
- Turning the system off
- Check of other sensors, e.g. smoke detector, room temperature gas-analyses, etc.

The stationary condition monitoring offers a reliable measure for the early and quick damage limitation. For example, heavy and expensive damages can be prevented by switching off on time.

After implementation of a risk analysis and estimating the damage potential, it can be decided about the type and scale of the monitoring system.

5.3 Practical Examples of Vibration Measurement

The damage diagnosis by condition monitoring and vibration analysis can be provided online, or if a disruptive incident had the destruction of the pump as consequence, made by the analysis of the recorded readings. But by accurate condition monitoring, a damage can be avoided completely.

Every type of pump has its own typical characteristic vibration. These vibrations change by different operating states like cavitation, dry run, etc., but also by faulty components on pumps, such as mechanical seal.

So with the help of speed, a clear vibration "fingerprint" can be created for every pump. Through this, it is possible to make a reliable statement about the general condition of the pump. Speed sensor see figure 86 [12].

5.3.1 Construction of the Measuring Technique

Different sensors are shown in the following.

Figure 85 Acceleration sensor

Figure 86 Speed sensor [12]

Figure 87 Thermocouple

Figure 88 6 channel-measuring box

The measuring chain for every parameter to be measured is configured as follows:
Test point – sensor – cable – measurement amplifier – PC

The acceleration sensor (see figure 85 [12]) measures the impact sound in terms of to the vibration analysis, the thermocouple (see Figure 87 [12]) is used for the temperature measurement.

Figure 89 Telemetry-transmitter [12]

With the help of a telemetry system (see transmitter figure 89, and receiver figure 90 [12]) the readings can be transferred cableless. The number of channels with the signals to be transferred is limited on the possibilities of the utilizable radio frequencies. The processing of the readings takes place with a measuring box (see figure 88 [12]) near to the pump. From there, the digital data can be transmitted with Ethernet up to 100 meters of distance to the main terminal.

Figure 90 Telemetry-receiver [12]

5.3.2 Avoidance of Measuring Errors

A measuring-error can completely destruct the monitoring or measurement. The measurement has either a spread of more than 10% or it is completely wrong. Depending on the application, an inaccurate measurement is hardly to reprocess and often useless.

By a measurement, it has to be paid attention to the following things:

- Right selection of the sensors
- Right positioning of the sensors
- High measuring frequencies, otherwise not all vibrations can be measured
- Noticing the instruction from the sensor manufacturer on the right calibration
- Suitable time intervals - averaging
- Using measuring amplifier if necessary
- Taking into account tolerances/range of fluctuation of the parameters to be measured
- Taking into account environmental conditions like temperature, air humidity, etc.
- Cost relevance of the precision
- Precision: as exact as possible but as exact as necessary

If several parameters, which were measured wrongly or inaccurately, have influence on the calculation, this leads to error propagation. At the wrong end result, then it cannot be comprehended anymore, where the mistake comes from. Only by laborious computation and follow-up measuring, the result can be corrected.

5.3.3 Analysis of Measuring Signals

After comparison of the measurements with the limit value data, conclusions arise about the operating condition of the pump:

Speeds

Normal operation:	The speed of the pump is in the rated range.
Inlet end closed:	The speed is increased.
Increased air amount:	The speed is increased strongly.
Cavitation:	The speed is increased absolutely very strongly.

Temperature Measuring

Normal operation: A normal temperature profile by warming up. The ball bearing heats up itself due to the friction. Due to flowing water in the pump the temperature of the mechanical seal remains constant.

Pressure side closed: Due to friction of the impeller with the water, the water temperature increases, since no fresh water can flow in. The temperature of the ball bearing increases through the warming of the casing.

Cavitation: not sufficient refrigerant water in the case, thus temperature of the mechanical seal and the ball bearing increases.

Dry run: Quick increase of the temperature in the mechanical seal visible.

5.3.4 Damage Diagnosis with the Help of Vibration Analysis

As already described in chapter 3.4.5 (pump monitoring) by the vibration diagnosis, the measured speed is additionally considered. The acceleration- or the impact sound-sensor measures the impact sound-vibration of the pump. As a measurement the acceleration is measured in g (9.81 m/s^2).

The analysis of the present operating condition of the pumps is carried out by means of frequency analysis. Moreover, the readings are loaded and FFT spectra are calculated (**F**ast **F**ourier **T**ransformation). Further, the level values and the speed are calculated according to the data format.

For every type of disturbance (dry run, cavitation, closed valve) a combination of limiting values, limiting curves, increasing values, characteristics can be determined. This makes it possible to diagnose the exact type of disturbance.

For the trend analysis for the maintenance cycles of the pumps, the measured data are recorded. The data from the past are completed with the current ones and illustrated and analyzed together, e.g. in 3-D-format. A group of disturbances is signalized before the error occurs, if given sizes are changing.

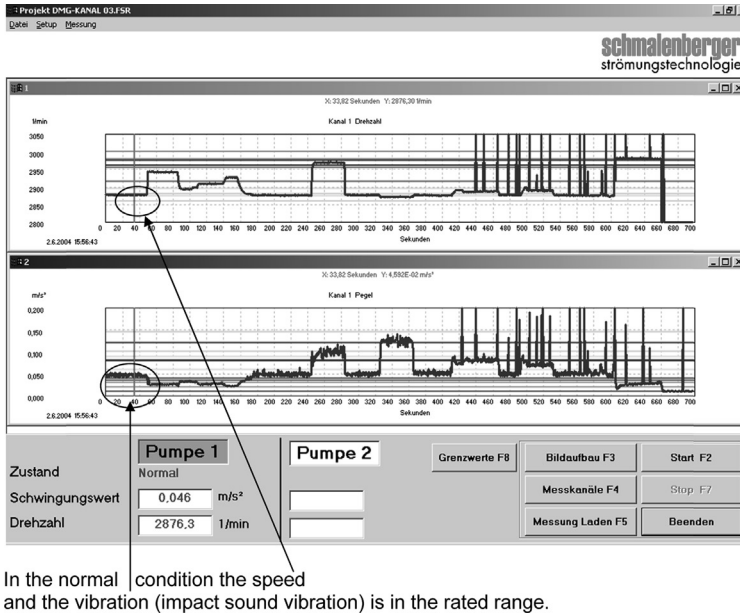


Figure 91 Pump in the normal condition (vibration and speed) [24]

In the above diagram see figure 91 [24], the speed and the vibration are illustrated. The plain text display “normal” states, that pump No.1 is in the normal condition and pump No.2 is switched off.

This system is a self-learning system. By the first machine-operation, the actual values of the pumps to be monitored are measured and recorded. A characteristic is made for every pump (disturbances are feigned and adjusted), a rated range of the parameters (green range) and a disturbance range (red range) are defined, so that later, the system immediately diagnoses the condition of the pump, i.e. type and dimension of the disturbance.

If the inlet end is closed, vibration and speed are higher than the rated value.

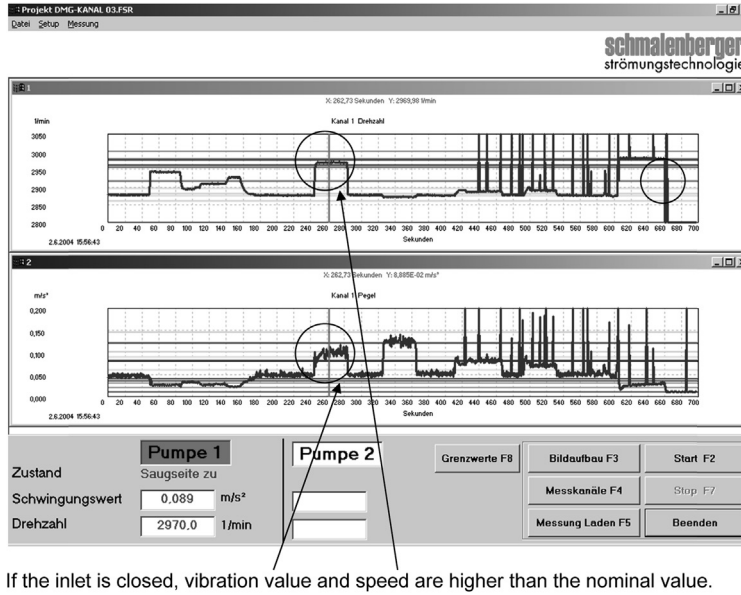


Figure 92 Operating condition: Inlet end closed [24]

In the operating diagram (see figure 92 [24]), speed and vibration are also illustrated. The plain text display "inlet end closed" states, that pump No.1 is in a disturbance condition. The measurements for vibration and speed are too high, they are above the values for the normal condition.

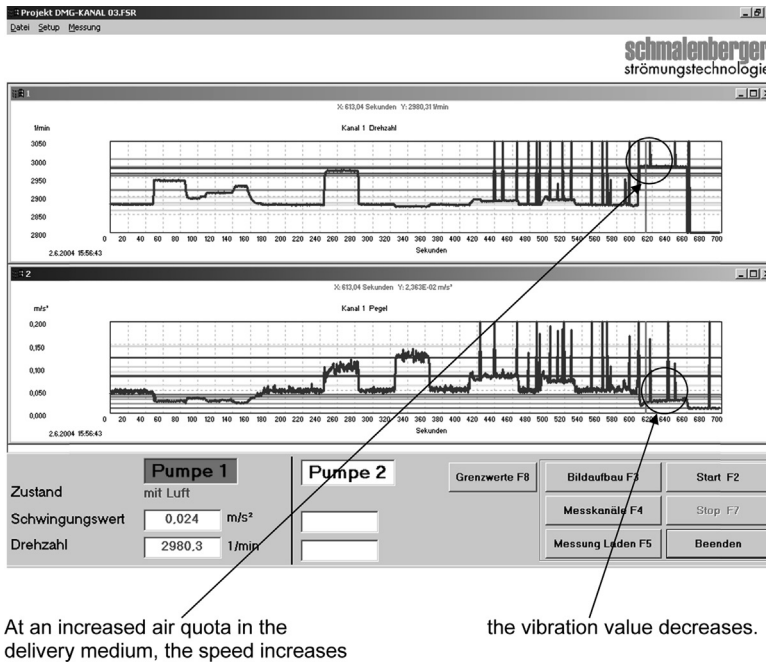


Figure 93 Operating state: increased air quota [24]

In the diagram “with air” (see figure 93 [24]) the plain text display “with air” states, that the pump is in a fault condition. The measurement for the vibration is too low, the value of speed is too high.

Telemetric Transmission

As already mentioned above, the readings can be transferred wireless with the help of a telemetry system. The sensors deliver analogous readings to the attached transmitting station, which is mounted near the pump. Before the telemetric transmission occurs, the analogous measuring signals are digitized and transferred in the MHz tape (megahertz) to the receiver. The telemetry receiver station is located at the measuring PC or at the PC-control station. The transferred digital readings are at first converted for the further processing and then written into a file or deposited in an allocated RAM memory. [12]

Impact Sound Measurements with Acceleration Sensors

In the following diagrams, the time courses of the values of the attached sensors with the different operating states or disturbances are shown:

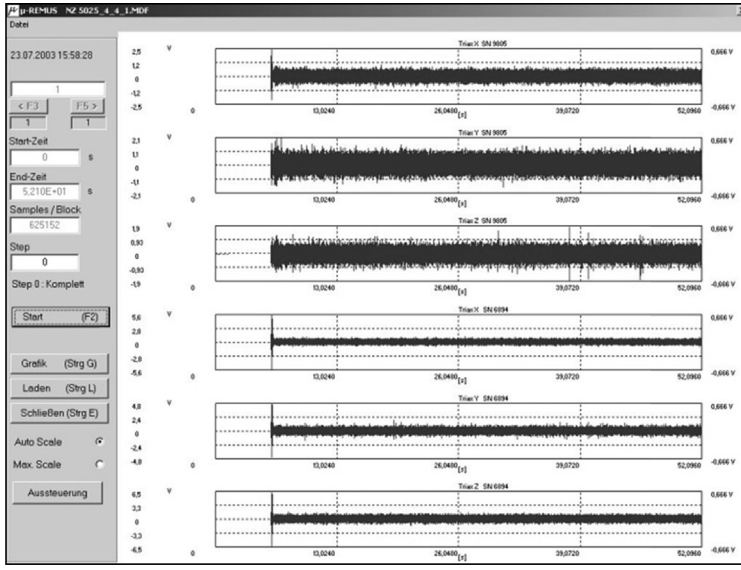


Figure 94 Normal condition [24]

The pump runs in the normal condition (see figure 94 [24]), the impact sound vibrations are constant and balanced.

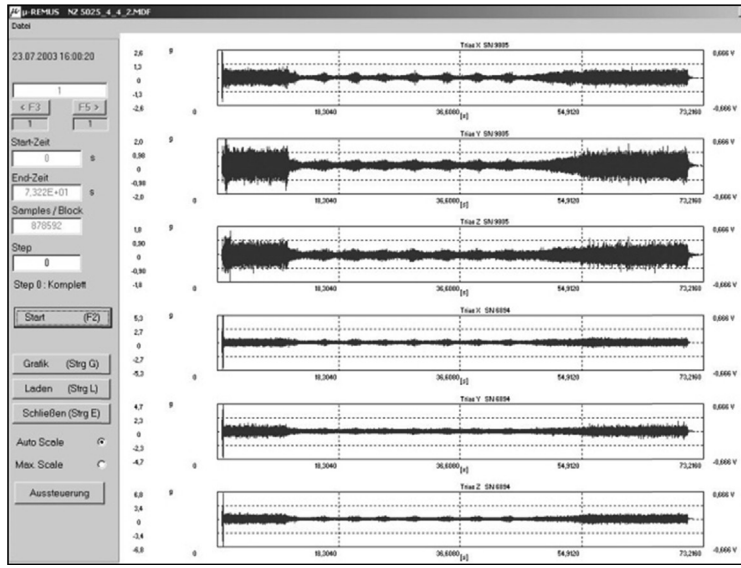


Figure 95 State with air [24]

The pump delivers air within the medium (fluid) (see figure 95 [24]), the impact sound vibrations are unbalanced and strongly fluctuating.

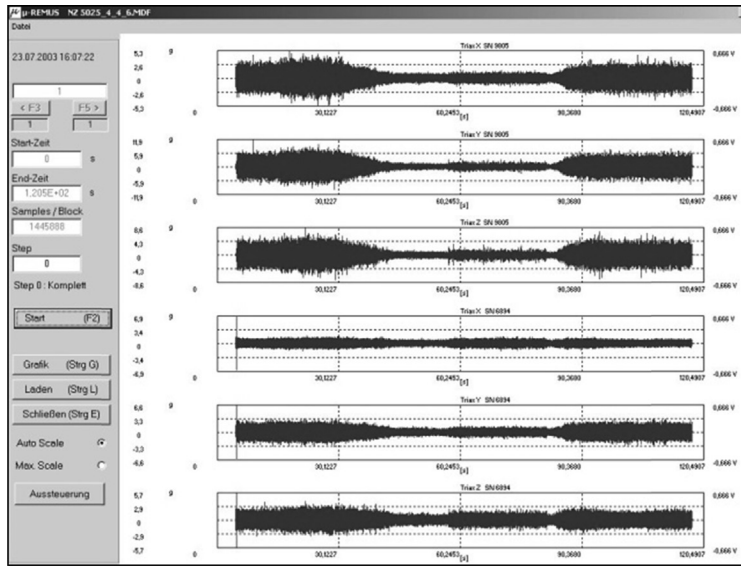


Figure 96 Cavitation [24]

The pump is cavitating (see figure 96 [24]). It comes to a local pressure lowering by over-speed and to vapor lock by evaporation of the delivery fluid. The impact sound vibrations are uneven, pulsating and with a high amplitude.

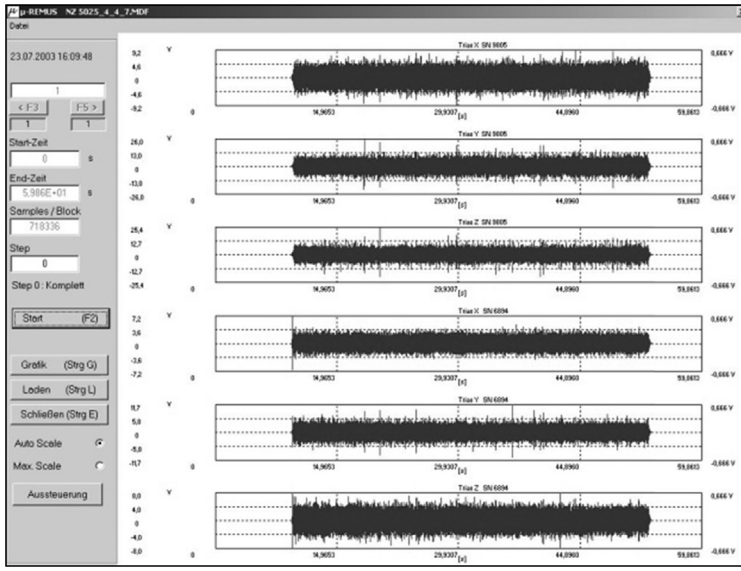


Figure 97 Pump runs backwards [24]

The pump runs backwards (see figure 97 [24]), it delivers fluid, but too little. The impact sound vibrations are relatively constant but with a high amplitude.

6 Advices for Planning and Conception of More Predictive Maintenance

A trouble-free operation of pump systems can be made possible by a future-oriented, intelligent maintenance strategy. Maintenance consists mainly of the basic measures servicing (maintenance), inspection, repairs and improvement in accordance with the Norm DIN 31051. The maintenance includes the operation of a pump system over the complete life cycle, from the first machine-operation up to the disposal.

While the maintenance includes basic measures like check, cleaning or also exchange of wear-out components, more extensive measures are carried out by the inspection. Data of the current state are compared with those of the nominal condition and possibly measuring of operation- pressure, temperature, electric current consumption, speed etc. are necessary.

By repair it is assumed, that the pump system is completely or partial out of order or there is a service-interrupting disturbance. Weak points or damages are cleared by this method. The improvement of maintenance means, increasing of the operational function of the system, so that interruptions or loss of productions are preferably avoided. On one hand this might mean the precautionary exchange of one or more components, or the realization of condition-oriented maintenance. With regard to the future, before damage enters, maintenance measures can be started by implementing continuous monitoring of the system. The measuring and recording of relevant parameters follows the analysis and evaluation and then the planning and implementation of measures.

Therefore, unforeseen disturbances and failures can be avoided, repairs can be minimized. Not but least, the saving of reserve pumps provides considerable economic advantages. About type and range of the monitoring system must be decided on the individual case, depending on application.

6.1 Monitoring of Pumps

Till now, the failure-oriented maintenance is still practiced. The pump is operated until the breakdown, only then, the worn out components are replaced. The time based maintenance contains precautionary, to replace the wear out relevant components regularly, even if they are not yet worn out.

Through condition-oriented, foresighted maintenance, standstill of systems, which means costs and loss of production, it is supposed to be avoided. Through careful work, carried out as a precaution and replacement of components, direct costs can be saved.

Damages on Pumps and Systems. http://dx.doi.org/10.1016/B978-0-444-63366-8.00006-1
Copyright © 2014 Expert Verlag GmbH. Published by Elsevier B.V. All rights reserved.

6.2 Diagnosis Systems

Both by selective inspection and by the online monitoring, the process consists of the following single steps:

- Measuring, recording, memorizing
- Calculating, evaluating, reviewing
- Illustrating, classifying, alarm diagnosing
- Measure-planning and -implementation

As already described in chapter 2, the special system-/ pump parameters must be registered and evaluated to plan suitable measures. Pressure, temperature, speed, or electricity gauges can be installed as stationary indicating instruments without further functions, for the regular inspection in the system. Furthermore for regular inspection, mobile diagnostic systems are implemented, which absolutely have also analysis functions besides the measuring functions. Process parameters like pressure, temperature or flow rate as well as vibrations, speed or unbalanced mass, are recorded and evaluated.

With a mobile equipment, signal analyses, trend notes, till complete machinery diagnoses can be prepared.

Through appropriate software, measurement tasks can be programmed. During the measuring, a comparison of the measured values with predefined limiting values is carried out. After recording and evaluation, it comes to the preparation of diagnosis reports.

Stationary diagnosis systems for the online condition monitoring, make sense for complex systems. Such systems combine recording, measuring, regulating and controlling (EMSR) up to the documentation of the results in one device.

On the monitoring terminals, the current system parameters, disturbances, alarms or other notes are notified for the maintenance personnel. By special maintenance software, informations and suggestions can be indicated, such like maintenance measures up to spare part provision.

The monitoring, together with documentation of all maintenance measures, makes an almost trouble-free operation of the systems possible. For the calculation of the profitability, effort and costs must be compared to the costs for loss of production and resultant damages. Since such systems also record trends and cause with regard to the future to avoid damages, often the technological effort is obviously justified.

6.3 Data Transmission

If it is a new plant, the data transmission is integrated into the network of the entire system for the pump monitoring or will be connected to a SPS control unit. Professional bus (Profibus) and Industrial Ethernet systems are far common below the variety of the common networks. Also via wireless communication systems (Profinet), the data can be transmitted. However, the most important factor by the

planning is, that the appropriate interfaces are available. Currently, important and far common systems are shown in table 16 [19]:

Table 16 Field-Bus Systems and Industrial Ethernet Systems

Industrial-Ethernet-Systems	Field-Bus-Systems
Ethernet/IP	Profibus
Profinet	CANopen
Ether CAT	Devicenet
SafetyNet	CC-Link
Powerlink	Modbus
Sercos	

To avoid, having to coordinate different systems with each other, it is advised, to use Profinet due to its universality and openness.

In the area of the motor drive, the Ethernet technology offers the possibility of exchanging the data in cycle time of the motor regulation, with the control unit in real time. Concerning the flexibility, Ethernet/IP and Profinet, are widespread in the drive technology.

6.4 Teleservice/Remote Maintenance

If once the servicing concept is integrated into an industrial network, the way to a teleservice- system is not very long. For example, Profinet permits to access to the data of a system via the web server, regardless of the location. If a remote diagnosis interface is available, the measuring signals of the sensors can be recorded and evaluated online. This creates the possibility of clearing smaller disturbances, without travelling expenses arising immediately. The complete diagnosis sequence of operations can so be managed, beginning with the recording of the measurements, the calculation and evaluation of the data.

The Ethernet technology therefore creates possibilities of assigning the monitoring and servicing tasks as an external service, by easily manageable costs.

6.5 Diagnosis and Maintenance as a Service Supply

To allocate maintenance and servicing externally, means nevertheless that the operator or owner of the plant knows his data for the pump system exactly. It is supposed that the critical areas or the system parameters being monitored, have to be known. Also previously it has to be cleared, if a regular inspection carried out in firm intervals is sufficient, or if the online monitoring makes sense.

Risks of failure and failure costs must be compared with the effort for the servicing. Staff costs and measuring equipment, arising in the house of the owner of the plant, are another criterion for the decision.

Table 17 Comparison: Inhouse Servicing or External Servicing

Criteria for Servicing/ Maintenance – Option	Maintenance Personnel of One's Own	External Maintenance by Service Providers
Trained specialist staff	+	++
Projectable fixed costs	+	++
Flexibility	++	+
The most modern measuring technique	+	+++
Risk appraisal	+	++
Reliable, periodic maintenance	+	++
Execution of small repairs	++	+

In general, external service providers have especially trained specialist staff and the measuring equipment corresponding to the state of the art. Both, full servicing and only individual modules offer the service providers. Whether only the monitoring or also complete repairs are assigned, this then must be decided by individual case. The conclusion of a maintenance agreement might be possibly a suitable solution for smaller enterprises. A comparison is shown in table 17 [T. Merkle].

7 Predictive Maintenance – Economic and Efficient

The economic feasibility of different measures orientates itself at the benefit and the costs arising out of the measures. However, decisive is the time period of the operation of the pump between going into operation up to the disposal. The cost pool for the investment is only by few pump systems more than 10% of the total costs, by most systems it's rather less. Costs for servicing, repair and energy predominate. Therefore a trouble-free energy optimized operation is very reasonable.

7.1 Best Efficiency Point

The optimal operating point adaptation is the simplest and most effective way of saving energy and costs. The difficulty often consists in investigating the system characteristic curve exactly, and in fixing the operating point consequently. In the optimal operating point, the pump has the best degree of efficiency, the optimal energy consumption, and is operated most gently, regarding the mechanical strain. The individual opportunities for the optimization were already described in chapter 3.1.3.

7.2 Energy Efficiency

Globally viewed, more than 20% of the world's electrical energy requirement is consumed by operating of pump systems. One aim is, to conserve resources and to counteract the energy shortage, on the other hand cost-saving by efficient pump operation opens great opportunities.

The efficiency of pump systems depends substantially on the kind of operation, which means adaptation of pressure and flow rate to the actual requirement. To be able to make a more precise statement about this, different types of costs of the system must be considered for the whole life cycle. An investigation of the VDMA (German association for machinery) showed, that the initial costs represent only about 10% of the life cycle costs, the energy costs, however, generate the greatest cost quota with more than 40%.

The use of energy saving motors can make a good contribution to the energy savings in the system. However, the speed control by frequency converters enables the three to fivefold of energy savings. However, the greatest reduction potential exists in the hydraulic optimization of the whole pump system.

Damages on Pumps and Systems. http://dx.doi.org/10.1016/B978-0-444-63366-8.00007-3
Copyright © 2014 Expert Verlag GmbH. Published by Elsevier B.V. All rights reserved.

For a more detailed estimation of the reduction potential, an analysis of the entire system must be carried out.

According to evaluation of the ZVEI (central association of electrical engineering and electronics industry in Germany) the energy reduction potential with electromotive driven systems constitutes as follows:

- energy optimized engines: 10%
- electronic speed control: 30%
- mechanical system optimization: 60%

Energy Optimized Motors

The attention increasingly turns to the efficiency or to the system effectiveness of the electrical drives. In accordance with the new EU-regulation 60034-30:2009, since June 16 th, 2011, the motors have not been evaluated any more after the EFF- classification, but subdivided to IE categories (International Efficiency).

This norm stipulates minimum efficiency factors of IE2 for three-phase motors Time schedule see table 18 [35].

Table 18 Time Schedule with Stages of the EU-Regulation for the Increase of Effectiveness at Electrical Motors [35]

Stages of the EU-Regulation No. 640/2009 (50 Hz) of the European Union	**Requirements**	**Notes**
Stage 1: **As of 16th June 2011**	The motors must fulfill the efficiency factors of IE2	IE2/high efficiency factor, comparable with EFF1 (European CEMEP agreement)
Stage 2: **As of 1st January 2015**	Motors with a nominal power of **7.5 - 375 kW** have to fulfill the efficiency class IE 3, or if they are equipped with a speed regulated drive, class IE2	IE3/premium- efficiency, derived from the class IE2 with ca.15% lower losses
Stage 3: **As of 1st January 2017**	Motors with a nominal power of **0.75 - 375 kW** have to fulfill the efficiency class IE 3, or if they are equipped with a speed regulated drive, class IE2	

The development in the direction of the energy efficiency of motors will go on continuously. The new EU-regulation states further, that three-phase motors of 7.5 kW up to 375 kW must either correspond to the higher efficiency class IE3 or be equipped with a frequency converter in the IE2 version from January 1st, 2015.

From January 1st, 2017, this regulation also concerns motors from 0.75 kW up to 7.5 kW.

These requirements technologically are released by different variants:

- More copper in the motors
- Motors with an integrated frequency converter
- Synchronous motors with permanent magnet

The use of energy optimized motors does not only make sense for energy saving reasons. For the operation of pumps which are often working for several decades, results also a considerable cost saving. Depending on pump size and operation hours per year, such pumps will have amortized themselves already after a few years.

Since the more effective motors develop less waste heat, in many cases no fan wheel is necessary. The optimization of the electrical winding also leads into improvement of the efficiency factor.

Special ball-/ antifriction bearings (Low-torque antifriction bearings) provide a 40-50% lower friction torque. The lower friction of the bearing enables often the choice of a smaller electromotor. An improvement of the efficiency factor by 1.5% seems to be realistic. A high efficiency motor is shown in figure 98 [30].

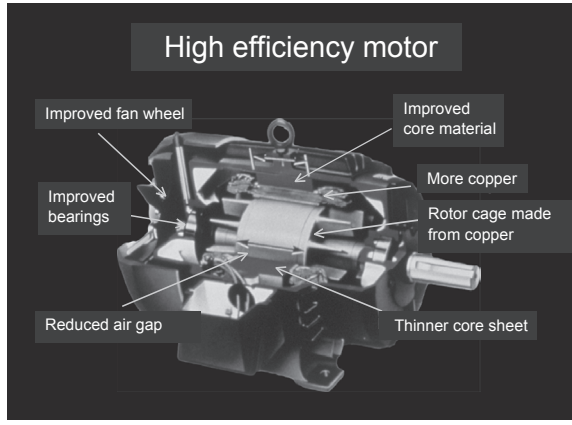


Figure 98 Opportunities of optimization at the electrical drive [30]

Based on the fact, that pumps in the future are equipped with much more effective motors, a further potential of optimization can be realized constructively.

Investigations showed, that regarding the pump hydraulics there is still absolutely potential. By improvement of the impeller surface, back plate and spiral casings, the efficiency factor can still be increased by some percent. Optimization of clearance and type of relieving (holes, etc.) make a further contribution.

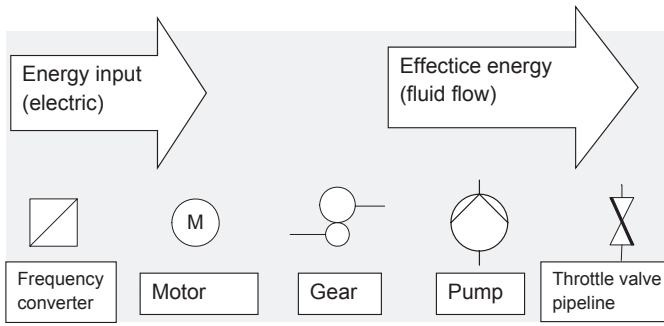
Well balanced impellers causes besides less noise level also a lower energy consumption.

The reduction of the wall thicknesses at the impellers causes a weight saving. By the low weight, the moment of inertia - Jw - will be reduced. Especially by frequent switching on/off, and as well at speed modifications, this brings saving of energy too.

By mechanical seals, the friction resistance can be reduced. This will be possible by smoothing of the touch surfaces and positioning a thin lubricating film between the slide surfaces. A raised friction resistance is converted into heat loss and reduces the efficiency. Diamond-coated mechanical seals are even better.

The expected "sum" of this energy savings by the component "pump" could yield +/– 10% improvement of the efficiency factor.

After the analysis of the component "pump", a complete system analysis of the pump system has to be carried out as shown in graphic 9 [30]:



Graphic 9 Single components of a pump system - optional [30]

Thus pump systems can often be very complex and sometimes containing very different components, by system analysis, each component must be examined separately. Each individual efficiency factor of a component affects the total pump efficiency significantly.

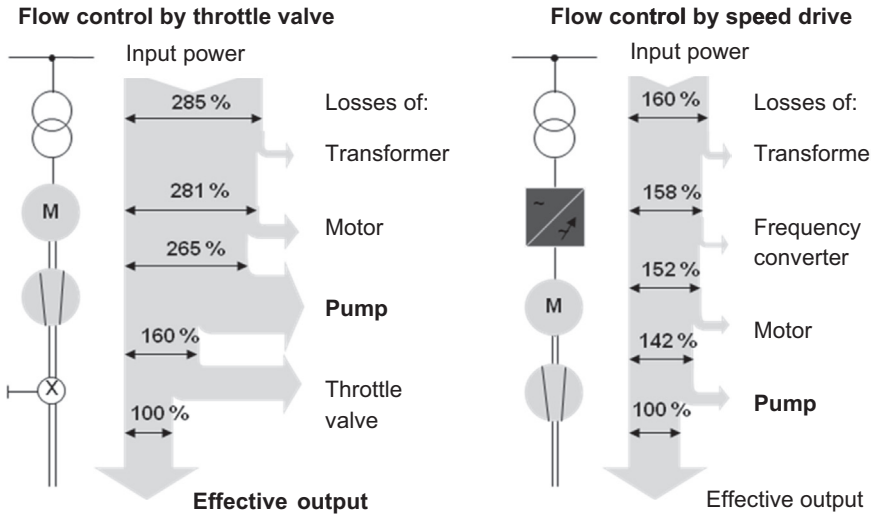
An optimal adjustment to the operating point can be realized by trimming of the impeller diameter and the use of frequency converters.

The process optimization (cascade system, exact definition of total head and delivery rate) offers - independently of the pump - a high reduction potential.

The pump power output or efficiency in comparison with the necessary electrical performance is represented in the graphic 10 [30]. Here, the effective output was set at 100%. Comparing the two energy flow diagrams, it is clearly to identify, that the main potential of savings is the process of the power unit.

By conventional throttle control, the 2.85-fold of the pump power output must be spent as electrical energy. The electronic speed drive demands however, only 1.6-fold.

Less energy consumption of the complete system could absolutely rise the system effectiveness about 30-35%. The improvement can be caused: by additional measures like an optimal adaptation of the operating point, optimization of piping and valves, speed control by frequency converters, as well as process optimization of the system.



Graphic 10 Comparison of throttle control with speed drive [30]

7.3 Life Cycle Costs

To be able to analyze the costs of pumps more precisely, it is necessary to carry through a total cost analysis. This consideration includes the calculation of the so-called "life cycle costs".

These aspects of TCO (Total Cost of Ownership) and LCC (Life Cycle Costs) are situated more in the focus on the analysis of the service life of a pump system.

The purpose of many operators is, buying pump systems where the complete costs can be exactly defined. Here, all costs like purchasing costs, operating costs, up to costs for disposal are taken into account and are exactly defined over a time period of 20–30 years.

In these life cycle costs (LCC), the costs for maintenance and repairs, and especially the availability of the system respectively contains the costs for the failure by standstill of the system.

This means, in the context of the TCO consideration, the value for the higher service life has influence directly on the economy calculation.

The multi investment into high-quality pumps with special coatings, energy-saving motors or intelligent controls, in most cases, it is much more economic, than the renunciation of it. The costs for repairs and failure of the pump systems are much higher.

The life cycle costs [LCC - Life Cycle Costs] consist in the sum as follows:

$$\text{LCC} = \text{sum of: } C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$

Where:

C_{ic} = initial costs (investment)
C_{in} = installation and putting into operation
C_e = energy costs

C_o = operating costs (running costs)
C_m = downtime, production loss
C_s = costs for maintenance and repairs
C_{env} = environment costs
C_d = closure and disposal

The main cost factors arise as the result:

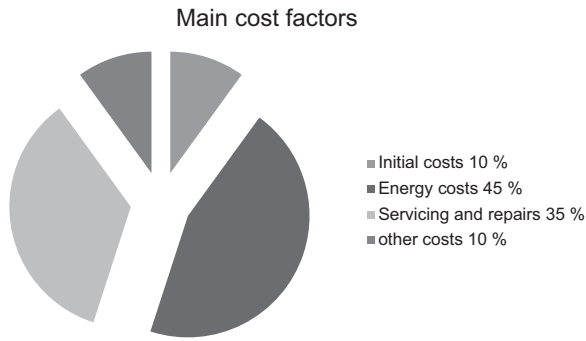


Diagram 25 Sectioning of costs at pumps

Initial costs (investment), maintenance, energy costs, other costs

By analysis of the cost quotas it is inestimable that the main attention must be focused on maintenance and energy consumption (see diagram 25). Solutions to this are: Wear out protection for the reduction of maintenance and repair, optimization of the energy consumption by frequency converters, hydraulic optimization of the system as well as energy optimized motors.

7.3.1 Initial Costs

Since the initial costs only make an impact of about 10% at the LCC consideration, the purchase price is less relevant than the other costs. If so an economical pump fails after 2 years and must be replaced, no costs are saved in comparison with a pump which is working for 15 years. The economy can be calculated with already available LCC software of different suppliers to carry out a comparison of individual pump varieties. So the purchasing price of a pump must always be compared to the other costs, especially costs for energy and maintenance.

7.3.2 Energy Costs

In comparison with the initial costs which once arise as a fixed amount (incl. discounting), the energy costs are very dynamic.

Although, energy costs are subject to fluctuations also, the tendency was and is, however, always increasing. At a quota of the energy costs of approx. 45%, this is the most critical factor of LCC, because the rate of price increases is only very difficult to anticipate.

Saving of energy by system optimization, using energy-saving motors or electrical speed control, is therefore economic in every case. The payback periods last here from some months up to some few years.

This is represented in detail in the following at two concrete examples (see table 19 [5]):

Example 1 Process Pumps:

Table 19 Costs- and CO_2 - Savings for a Pump System [5].

Before the Optimization	**After the Optimization**
Control: Bypass + throttle valve	Frequency converter
Oversized pump, 18,5 kW	Energy efficient pump, 1,5 kW
Electricity consumption: 57 000 kWh	Electricity consumption: 5 590 kWh
	Investment: 3 800,- €
Costs of electricity: 6840,- €	Costs of electricity: 670,- €
Reduction of the electricity consumption: 51 410 kWh/Jahr	
Cost reduction: 6 170,- €/year (by cost of electricity of 12 cent/kWh)	
CO_2 - reduction: 33 t/year (by German electricity mix: 633 g CO_2/kWh)	
Payback period: < 1 Jahr	

Example 2 Process Pumps (27 Pump Systems Approx. 2 500 Pumps, see table 20 [5]):

Table 20 Costs- and CO_2 - Savings at More Pump Systems [5].

Before the Optimization	**After the Optimization**
Control: Bypass + throttle valve	Frequency converter
Oversized pumps	Energy efficient pumps, IE2-motors
Electricity consumption: 2 305 000 kWh	Electricity consumption: 1 678 530 kWh
	Investment: 111 530,- €
Costs of electricity: 276 600,- €	Costs of electricity: 201 424,- €
Reduction of the electricity consumption: 626 470 kWh/Jahr	
Cost reduction: 75 180,- €/year (at cost of electricity of 12 cent/kWh)	
CO_2 - reduction: 400 t/year (at german electricity mix: 633 g CO_2/kWh)	
Payback period: ca. 1,5 years	

By the replacement of the throttle control or the bypass control through a speed control with frequency converter, the efficiency of the pumps can be increased by some per cent.

7.3.3 Servicing and Repairs

Qualitatively good pumps have in many cases higher prices, however usually the pumps are maintenance-free and less vulnerable to failure.

However, periodic maintenance in accordance with the given maintenance schedule helps to minimize the total costs. Especially for critical or complex systems, a foresighted maintenance is highly recommended. Suitable condition monitoring systems (C.M.) are already available on the market. Disturbances, which means costs, can at long last be avoided. Also here, the economy or the period of amortization can be calculated by means of LCC software.

7.3.4 Other Costs

Another tenth of the total costs can be summarized under the factor "other costs". These are costs for adjustment/putting into operation, operating and environment costs as well as costs for production loss during disruptions.

An installed condition monitoring system, which helps avoiding disturbances and subsequent loss of production, has amortized itself in most cases very fast. Costs for closure and disposal do not have an effect so much at a long life time of a pump. But indeed on a short life time.

7.3.5 Software for LCC Calculation

Different software systems for the LCC calculation are already available on the market.

- Ball bearings: http://bearinx-online-easy-friction.schaeffler.com
- Systems: www.world-class-manufacturing.com
- Pump systems: www.system-energieeffizienz.de
- Pumps/electrical drives: www.zvei.org/Lebenszykluskosten

The life cycle cost calculator for pumps makes it possible, also to compare the systems with different load profiles and capacity profiles. In the program, different operation parameters can be entered for the calculation of different pump systems. The calculation result is a cost value, which allows to compare the life cycle costs of the systems for selecting the most favourable. In most cases, not the system with the lowest investment costs is the most economical one, but the system with the lowest energy- and maintenance costs will be the most favourable.

7.3.6 Summarizing Consideration the LCC

Costs for maintenance and energy represent together approx. 80% of the total costs.

Low-maintenance pump systems, which usually are more expensive in the acquisition but comply with higher quality standards are certainly quite worthwhile. Implementation of energy-saving measures, especially by pumps in the continuous operation is part of the most effective system optimization.

The costs for energy and material will definitely increase within the next years. On one hand, the energy costs are incorporated directly into the costs for the operation of a pump system per running hour or per annum. But since material processing, for example producing a cast case or the copper winding of an electromotor is energy consuming too, increasing energy costs also have an effect on the manufacturing costs, and therefore just multiple negative.

Moreover by other products already regarded as the parameter “pay back time”, will be paid attention. This means the time period, in which an improved pump system amortizes itself. Only due to growing material shortage, will the material prices increase. The costs which are dependent on the energy costs, like extraction, transportation and processing have to be added.

Recyclable products with re-usable materials, will receive more significance. The more recyclable a pump is, the higher their residual value will be at the time of the disposal. This means by purchasing a pump, the investment costs will be viewed more under the aspect of the recycling value.

7.4 Cost Increase and Material Shortage

Damages and wear out are always related to material consumption, costs and lastly energy consumption. Therefore, that’s why it is important to have the whole consideration. Increasingly, materials which are reusable will be used for the products. Energy costs will increasingly determine the design of the products.

7.4.1 Rise of Energy Costs

Within the last few years the energy costs have risen continuously. The stagnating or relieving crude oil production indicates a shortage of the oil reserves. The prices for energy increased extraordinary to never existing amounts in 2008, a year with a very high economic growth. The price of crude oil was at U.S. $140 per barrel in June 2008. After a decrease in the year 2009, the peak almost was reached again in 2011 (see diagram 26).

Scientist of the union “Association for the study of Peak Oil” expects a strongly declining crude oil production in the future. Therefore, the prices of energy will rise continuously and affect the production costs of pumps directly (see diagram 27).

7.4.2 Costs of Materials

The costs of material represent with more than 45% in the producing industry still in front of the personnel expenditures, the largest cost block bloc. While the labour productivity could be increased around the factor 3.5 since the year 1960, the development of the material productivity remained far back (factor 2). Studies have shown, that a 20 per cent increase of the material efficiency seems practicable up to the year 2015 (see diagram 28 [4]).

Since the costs of material are immediately bound up with the costs for transportation, energy and disposal, here, the potential for savings at an improvement on the material efficiency is very high.

Using material efficiently means both, to minimize the waste and offcut during the manufacturing of the products, and to optimize the completed product with regard to the material usage.

Modern computer-simulation tools offer here various possibilities to reduce wall thicknesses.

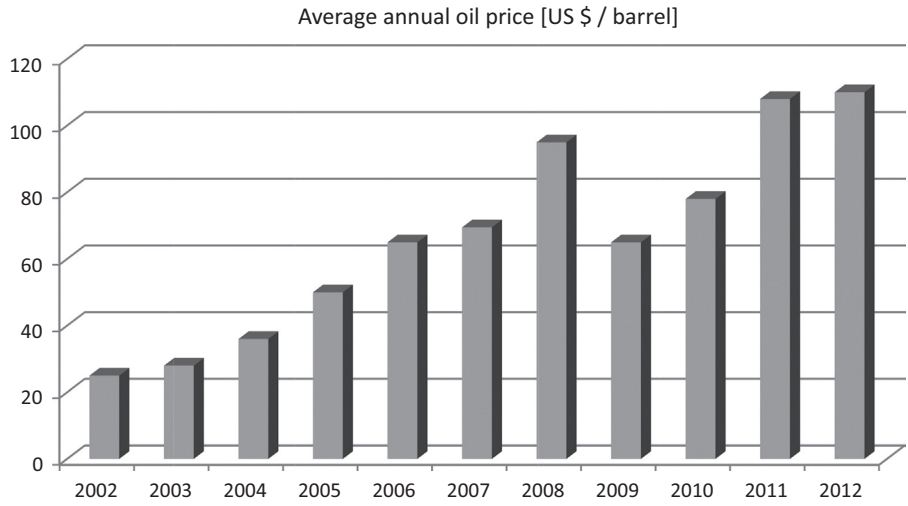


Diagram 26 Average annual oil price in U.S. $ per barrel

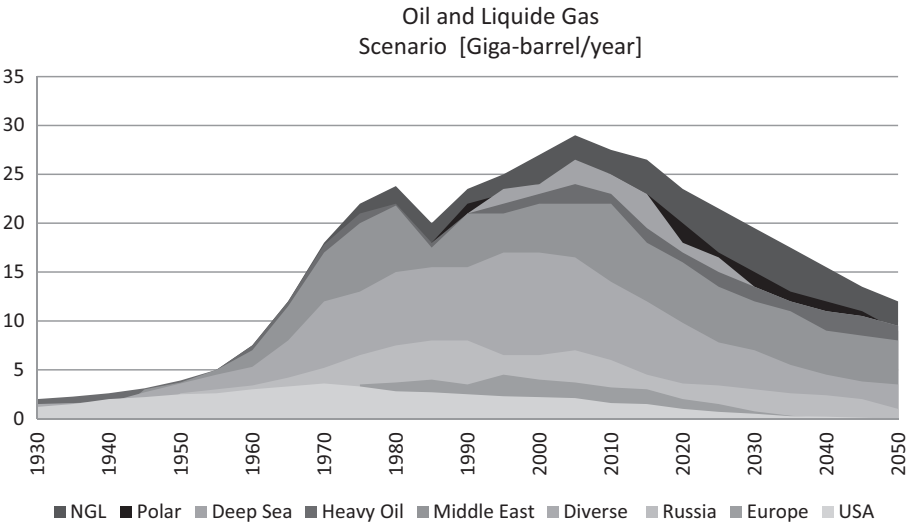


Diagram 27 Worldwide decreasing delivery of oil and liquefied gases, 1930-2050

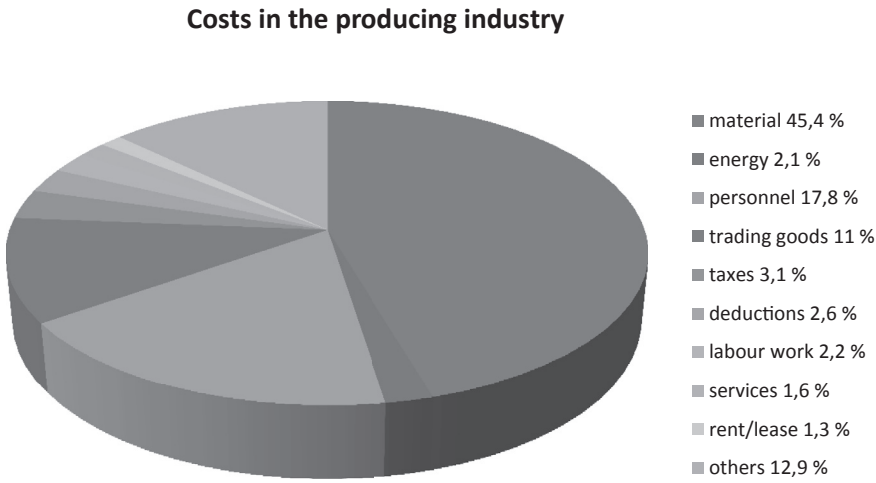


Diagram 28 Cost structure in the producing industry, [www.demea.de]

Production methods and product design must be adapted to the optimized material deployment.

In comparison with the costs for staff and energy, the costs for material have risen continuously within the last few years. On the one hand there is potential for savings,

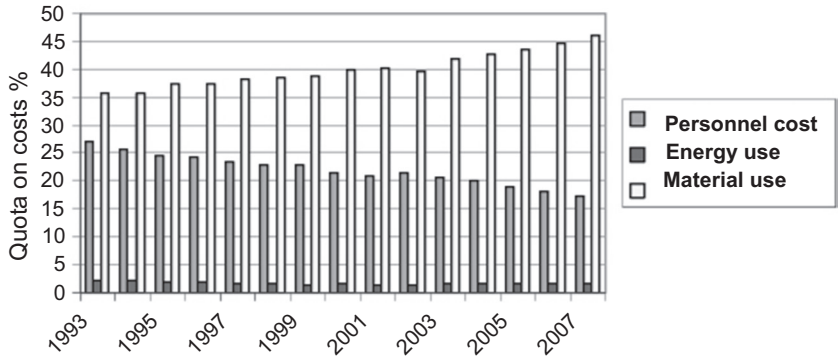


Diagram 29 Cost quotas material, energy, staff [source: statistical Federal Office]

on the other hand it is very important to organize the material usage in a way, that the products or pumps are able to work relatively long enough without breakdown and wear-out (see diagram 29 [10]).

However, to minimize damages to pumps, high-quality wear-out resistant materials are recommended. Having a view to the life time of the pump, where the initial

costs represent the smaller quota, this clarifies that the investment into a high-quality, long-lasting and low-maintenance pump is worthwhile.

7.4.3 Recycling of Materials

Increasing energy and material prices will in future more and more determine the mode and the type of the pumps and systems.

Consequently, pump components made of the metals like steel, copper and aluminum will have to be long-lasting and recyclable. After the disposal, they will be carefully dismantled, put in pieces into their components and recycled. Even the components of the electro-motors will also be put into pieces and then reused.

Components made of synthetic/plastics material will only be competitive in future, if either they are very economically produced and disposable or fully recyclable.

The material shortage will lead to the fact that an increase of service life means more cash money than before. To avoid the loss of production by a well operating pump system will lead to even higher cost savings than before.

Used Formula Signs and Units

H	Total head
H_{stat}	static total head quota (plant)
H_{dyn}	dynamic total head quota (plant)
J_W	Moment of inertia
η	Efficiency factor
P	Power output
Q	Capacity (delivery rate)
p1	Pressure at the inlet side (suction)
p_{amb}	Air pressure
p_v	Vapour pressure
V_1	Flow speed at the inlet side (suction)
z_s	Geodesic height related to the datum plane
ρ	Density of the delivery fluid
g	Local acceleration of gravity

Units

A	Amperage
1/min	Rotation speed
rpm	Rounds per minute
bar	Pressure
°C	Temperature
f	Frequency (Hz)
HV	Harden in Vickers
K	Unit for temperature difference
kg/m^3	Solid matter quota
kg/l	Solid matter quota
kW	Performance / motor output
mg/l	Cl-Ion quota (Chloride)
m/s	Flow speed
m/s^2	Gravity (9,81 m/s^2)
N/mm^2	Tensile stress (Elastic modulus)
µm	Layer thickness
m^3/h	Flow / flow rate
V	Voltage

Bibliography

[1] Schmalenberger GmbH + Co. KG, internal papers, Balasz-Klein I. Steigerung der Energie-Effizienz von Kreiselpumpen – Untersuchungen zur hydraulischen und antriebstechnischen Optimierung. Bachelor-Thesis. Hochschule Reutlingen; 2010.

[2] Bohl W, Elmendorf W. Technische Strömungslehre. Würzburg: Vogel-Verlag; 2008.

[3] Bosch Rexroth AG. Rexroth Praxisseminar - Elektrische Antriebe 2005. Lohr, 2005.

[4] demea; Basisinformationen, warum ist Materialeffizienz wichtig. Berlin: Deutsche Material-effizienzagentur (demea); 2011. www.demea.de.

[5] dena; Erfolgsbilanz bei Pumpensystemen: Energieeffizienz lohnt sich. Berlin: Deutsche Energieagentur; 2007.

[6] dena; Contracting, Betriebsführungs-Contracting. Berlin: de, Deutsche Energieagentur; 2011. www.energieeffizienz-im-sevice.

[7] DIN 31051; Grundlagen der Instandhaltung, Deutsche Norm. Berlin: Deutsches Institut für Normung; 2003.

[8] DIN 50902; Korrosionsschutzschichten und ihre Herstellung, Deutsche Norm. Berlin: Deutsches Institut für Normung; 1994.

[9] Edelstahl Rostfrei - Eigenschaften; Merkblatt 821, Informationsstelle Edelstahl Rostfrei. Düsseldorf 2006.

[10] Energieeffizienz. Ministerium für Umwelt, Klima und Energiewirtschaft Baden Württemberg. de, Stuttgart; 2011. www.umweltschutz-bw.

[11] Kalenborn; Verschleißschutz für Anlagenkomponenten und Rohrleitungen, Kalenborn Kalprotect Dr. Mauritz GmbH & Co.KG, Vettelschoss.

[12] Hastrich HP. Schäden an Pumpen und Pumpensystemen. Esslingen: Seminar-Manuskript Technische Akademie Esslingen; 2010.

[13] Henzelmann T, Büchele R. Der Beitrag des Maschinen - und Anlagenbaus zur Energieeffizienz; Roland Berger Strategy Consultants. Frankfurt a.M: Studie im Auftrag des VDMA; 2009.

[14] Isecke B, Mietz J. Vermeidung der Korrosion nichtrostender Edelstähle in chlorid-belasteter Schwimmhallen-Atmosphäre, Dokumentation 882. Düsseldorf: Informationsstelle Edelstahl Rostfrei; 2001.

[15] Lenze; Dezentrale Antriebstechnik. Hamelin: Lenze Automation GmbH; 2011.

[16] Liedtke D. Nitrieren und Nitrocarburieren, Seminar-Manuskript. Esslingen: Technische Akademie Esslingen; 2005.

[17] Merkle T, Reuschel A, Schmauder S. Hart im Nehmen - Prozesssicherheit durch Verschleißschutz, Verfahrenstechnik. Mainz: Vereinigte Fachverlage; 2010.

[18] Merkle T. Verfahren und Vorrichtung zur Überwachung von Pumpenanlagen. München: Patentschrift DE 10 2004 028 643; 2005.

[19] Moxa Europe GmbH. Aus der Ferne überwachen – Echtzeit-Statusüberwachung im Ethernet-Netzwerk, messtec drives Automation. Weinheim: GIT-Verlag; 2011.

[20] Piesslinger-Schwaiger S, Zahel H. Höhere Korrosionsbeständigkeit von Edelstahl durch Polinox Protect und Polinox Protect TC. München: Poligrat AG; 2011.

[21] Process-Seminar; Pumpenseminar, Störungsfrüherkennung. Würzburg: Vogel-Verlag; 2005.

[22] Prognos AG. Energieeffizienz in der Industrie – eine makroskopische Analyse der Effizienzentwicklung unter besonderer Berücksichtigung der Rolle des Maschinen- und Anlagenbaus. Berlin: Studie im Auftrag des VDMA; 2009.
[23] Reuschel A, Merkle T, Schmauder S. Dem Verschleiß auf der Spur; Process 3–10. Würzburg: Vogel-Verlag; 2010.
[24] Schmalenberger GmbH + Co. KG; interne Schriften und Berichte 2003 – 2011.
[25] Sigloch H. Technische Fluidmechanik. Berlin: Springer-Verlag; 2008.
[26] Sigloch H. Strömungsmaschinen. München: Carl Hanser-Verlag; 2009.
[27] Siemens AG. Energieoptimierung für Industrie und Infrastruktur. Erlangen, 2008.
[28] Solid Works; Flow Simulation Tutorial, solidpro GmbH. Seligenstadt, 2011.
[29] Solid Works; Sieben Kerntechnologien der Flow Simulation, solidpro GmbH. Seligenstadt, 2011.
[30] Steins D. Betriebskosten senken mit Energiesparmotoren. Düsseldorf: Deutsches Kupferinstitut; 2011.
[31] Todorov V. Neue Materialien zur Erhöhung der Verschleiß - und Korrosionsfestigkeit von Kreiselpumpen, Studienarbeit, Institut für Materialprüfung, Werkstoffkunde und Festigkeitslehre. Stuttgart: Universität Stuttgart; 2005.
[32] VDI-Richtlinien. VDI 3822, Schadensanalyse; Grundlagen und Durchführung einer Schadensanalyse. Düsseldorf: VDI; 2010.
[33] VDI-Richtlinien. VDI 3832, Körperschallmessungen zur Zustandsbeurteilung von Wälzlagern an Maschinen und Anlagen. Düsseldorf: VDI; 2007.
[34] VDMA. Der Beitrag des Maschinen - und Anlagenbaus zur Energieeffizienz. Frankfurt a.M 2009.
[35] VDMA. Pumpen Lebens-Zyklus-Kosten. Frankfurt a.M 2003.
[36] Verschleißbeständige weiße Gusseisenwerkstoffe – Zentrale für Gussverwendung, Düsseldorf.
[37] Verordnung (EG) Nr.640/2009 der Kommission zur Durchführung der Richtlinie 2005/32/EG des Europäischen Parlaments und des Rates im Hinblick auf die Festlegung von Anforderungen an die umweltgerechte Gestaltung von Elektromotoren. Brüssel 2009.
[38] Volz M. Nicht alle Industrial-Ethernet-Systeme werden sich am Markt durchsetzen, messtec drives Automation. Weinheim: GIT-Verlag; 2011.
[39] Vortmann C. Untersuchungen zur Thermodynamik des Phasenübergangs bei der numerischen Berechnung kavitierender Düsenströmungen. Karlsruhe: Universität Karlsruhe; 2001.
[40] Wagner W. Rohrleitungstechnik. Würzburg: Vogel-Verlag; 2008.
[41] Wagner W. Kreiselpumpen und Kreiselpumpenanlagen. Würzburg: Vogel-Verlag; 2009.
[42] Wärmebehandlung von Stahl – Nitrieren und Nitrocarburieren; Merkblatt 447. Düsseldorf: Stahl-Informations-Zentrum; 2005.
[43] EagleBurgmann Germany GmbH & Co. KG, Werksbüro Stuttgart, 2014.
[44] Kavitation an einem Tragflügel; Universität Stuttgart Institut für Strömungsmechanik und Hydraulische Strömungsmaschinen, Stuttgart.

Index

Note: Page Numbers followed by *f* indicate figures; *t*, tables; *b*, boxes.

A

Abrasion, 4–13, 78–80
Antifriction bearings, 8, 117
Anti-corrosion protection, 75–78

B

Bentonite, 5b–6b
Bernoulli, 62
Blasting, 72
Boundary layer, 62–63
Bright annealing, 72
Brushing, 71
Bus systems, 113t
Bypass control, 37, 44t, 121t

C

Carbides, 16, 16t, 85
Carbon layers, 90–91
Cascade circuit, 39–45, 39f–40f
Cast iron materials, 85t
Causes of wear, 1–4, 20–22
Cavitation, 13, 13f–14f, 48–52, 49f, 60, 105, 109f
CFD. *See* Computational fluid dynamics (CFD)
Cleaning with wire needle, 72
Cloud cavitation, 50
Computational fluid dynamics (CFD), 23, 65, 68, 80
Condensation technique, 72–73
Condition monitoring, 28–29, 54–62, 55f, 99–101, 122
Contracting, 61–62
Corrosion, 10–13, 72–73, 83f
Current measurement, 28

D

Damage images, 25, 29
Data transmission, 112–113
Delivery head, 47, 51
Delivery rate, 39, 118
Diagnosis systems, 112
Diamond similar layers, 91–92
Dry run, 19f
Dry run protection, 52–54
Decrease in pressure, 9, 13

E

Economy, 120
Energy efficiency, 115–118
Energy equation, 62
Energy payback times, 121
Ethylene-Tetrafluorethylen (ETFE), 74t
Ethernet, 112–113, 113t
Evaporation germs, 49

F

Failure analysis, 28–29, 79f, 86
Field bus, 113t
Fault management, 56
Flame cleaning, 72
Flow losses, 37, 63
Flow rate, 38–45
Flow simulation, 23–24, 65–67, 80, 93
Frequency analysis, 29, 105
Frequency converter, 118, 37, 41, 44–45

G

Grinding, 72
Grinding sand, 10–11

H

Hard cast, 85

I

Inducer, 96–97
Inorganic layers, 72
Implosion, 49

J

Jamming chamber, 53, 53f

L

Laminar flow, 62
Laser surface cladding, 88–90
Layer cavitation, 50
Life cycle costs (LCC), 119–123
Leakage, 14
Limiting value investigation, 100
Losses, 37, 62–65

M

Machine diagnosis, 106, 112
Maintenance, 111, 113–114, 122
Mechanical seals, 14–19, 49f, 53
Motors, 116–118, 116t

N

Net positive suction head (NPSH), 51
Nitriding, 73, 86, 87f
Nitro-caburisation, 87
Noise emission, 20
NPSH. *See* Net positive suction head (NPSH)

O

Operating point, 31–47, 45f, 118
Organic layers, 72
Overload, 3

P

Parallel operation of pumps, 33, 34f
Passive layer, 11, 75
PFA, 74t
Pitting corrosion, 11, 76f
Plasma nitriding, 87
pH-factor, 80
Pipeline losses, 63–65
Profibus, 112–113
Profinet, 112–113
Pourbaix diagram, 11
Pressure loss, 31
Pressure measurement, 28
Pump operation map, 32f
Pump selection program, 36f

Q

Q-H-characteristic, 32

R

Resonance noises, 21t
Rubber coatings, 84–85

S

Seawater, 1, 11–12
Series operation of pumps, 35
Shark skin surface, 7f, 8
Shaving, 72
Silicon carbide, 5b–6b, 16–17, 78, 91
Sliding materials, 16–17
Slurry, 5b–6b, 6
Solid matter particle, 8–10
Solid particles, 1, 8–9
Speed control, 37, 39–45, 115
Speed measuring, 28
Surface preparation, 71–72
Surface reimbursement, 86–93
System characteristic, 32–36, 33f, 41t

T

TCO. *See* Total cost of ownership (TCO)
Telemetry, 103, 103f, 108
Teleservice, 61, 113
Temperature measurement, 27–28
Thermocouple, 27, 102f
Total cost of ownership (TCO), 119
Turbulent flow, 11, 62
Trend analysis, 105
Trimming curves, 45
Throttle curve, 33f
Throttle control, 44t, 118, 119f
Tungsten carbide, 16, 16t

U

Unbalance of impellers, 109, 112

V

Varnish water, 25, 25f
Vibration measuring, 27, 101–110
Vibration analysis, 28–29, 105–110
Viscosity, 46–47
Volume flow rate, 32

W

Wear out, 1–13, 81–82
Wear out simulation, 68–70
White cast iron, 85
Wolfram carbide, 16, 78