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Process Fluid Analysis in Heat Pump and Water Chiller Life Cycle Management

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<p>Adequate maintenance and life cycle management are essential in maintaining optimal operation conditions for any equipment. This thesis covers process fluid analysis as a part of heat pump and water chiller life cycle management. The aim of this thesis was to recognize the most important equipment and fluid condition indicators in the process fluids used for heating and cooling applications.</p> <p>During the scope of this thesis the main reasons and mechanisms for corrosion and contamination in heat pumps and water chillers were discussed. Main indicators for corrosion and contamination were set according to existing literature and research about the subject. Also limit values for the main parameters were set following the guidelines of various studies. In the practical part of this thesis recommendations were given about the extent of personnel training, best sampling methods and results reporting for the customer. During the scope of the thesis also a cost analysis for the chosen methods for process fluid analysis was conducted. Possible setbacks and issues concerning the chosen methods were discussed, and it was decided that the service should be piloted prior to marketing for all of the Company's customers.</p> <p>This thesis includes mainly the initial research and recommendations for systematic and inclusive process fluid analysis. Because of the initial nature of this study, many practical points need further discussion prior to the launch of the new service.</p>	
Keywords	Heat pump, water chiller, fluid analysis, process condition monitoring

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<p>Asianmukainen huolto ja elinkaaren hallinta ovat olennaisia osia minkä tahansa laitteen optimaalisessa ylläpidossa. Tämä opinnäytetyö käsittelee lämmitys- ja jäähdytyslaitteiden prosessinesteiden ominaisuuksien monitorointia osana lämmitys- ja jäähdytyslaitteiden elinkaaren hallintaa. Tämän työn tarkoituksena oli tunnistaa ne parametrit, jotka ovat olennaisimpia lämmitys- ja jäähdytyslaitteiden prosessinesteiden onnistuneessa monitoroinnissa.</p> <p>Tässä opinnäytetyössä määriteltiin korroosion ja kontaminaation pääasialliset syyt ja mekanismit lämmönsiirtokoneikoissa. Alan kirjallisuuteen ja tutkimuksiin perustuen näille koneikoille määriteltiin myös korroosion ja kontaminaation havainnointiparametrit, sekä näiden parametrien raja-arvot. Työn käytännön osuudessa määriteltiin suositukset henkilöstön kouluustarvetta, parhaita näytteenottotapoja ja asiakasraportointia varten. Työhön sisältyy myös kustannusanalyysi valituille toimintatavoille sekä näytetesteille. Työssä arvioitiin myös prosessinesteiden kunnan monitorointiin valittujen toimintatapojen mahdolliset huonot puolet sekä toimintatapoihin liittyvät mahdolliset ongelmatilanteet. Ongelmatilanteiden ehkäisemiseksi tultiin päätökseen, että palvelu pilotoidaan ennen yleistä markkinointia.</p> <p>Tämä opinnäytetyö sisältää alustavan tutkimuksen ja suunnitelman uuden palvelun käyttöönottoa varten. Koska kyseessä on alustava suunnitelma, on mahdollista että tässä työssä esitetyt prosessinesteiden kunnan parametritsekä toimintatavat muokkautuvat vielä palvelun käyttöönottovaiheessa.</p>	
Keywords	Lämpöpumppu, vedenjäähdytin, nesteanalyysi, prosessin tilan monitorointi

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Foreword

Some of the statements and findings in this thesis are based on the Company's internal database's documents and data sheets, which are not public material, or on interviews of the company's own experts. These statements are clearly indicated for the reader to be able to differentiate them from literature based data. Where possible, supporting and/or contradicting sources have been used to argue the technical reliability of these statements.

7th of November 2014

Tarja Ruoho

1 Introduction

As all equipment, also heat pumps have a restricted life time and after certain hours of operation are bound to face the end of their life cycle. Failures due to component wear and malfunctions in internal equipment such as pumps and compressors, among electrical component malfunctions, are the most common reasons for heat pump failures [1, 2].

All equipment with moving parts, or rather all moving parts in the equipment, is subjected to wear since the beginning of operation. Mechanical wear is introduced when a moving surface is in contact with another surface; regardless if the surface is large (piston inside a compressor) or small but large in quantity (metal particles through a pump), or even a liquid [3].

Typically, there are four liquids present in a HACR¹ system: water, refrigerant, coolant and some type of lubricant. Lubrication is used in order to minimize the mechanical wear in the equipment, whereas water and coolant are used for heat transfer. [4] However, the presence of liquids in the system often promotes wear through corrosion or cavitation. The reasons and mechanisms for the aforementioned are described into more detail in chapter 3 of this thesis.

According to various studies, the presence of certain substances in process liquids has been proven to be an effective way of determining the overall condition of the heating and cooling system. By analysing the content of metals in lubrication oil it is possible to recognize the early signs of component wear before any malfunctions occur; coolant analysis on the other hand can provide vital information on the possible performance issues of the system and even pinpoint the most likely source for the problem. [5, 6]

The purpose of this thesis is to determine the most cost-efficient yet still descriptive analyses and indicators for the process liquids used in the Company's applications, and utilize the findings to make recommendations for providing maintenance services to the company's customers. The theoretical part of the thesis will focus on literature

¹ Heating, Air Conditioning and Refrigeration

research of the most significant indicators in process liquid analyses. During the thesis also the best sampling methods will be determined.

After literature review the practical setups needed for launching the new service are presented in the thesis; these will include description of the personnel training needed in order to be able to give out reliable interpretations of the condition of the process, as well as suggestions related to marketing of the service and reporting results to customers. Also the cost analysis of the service will be presented in the practical section of the thesis.

Possible drawbacks of the methods chosen for the analyses as well as possible misinterpretations related to the process state indicators will be discussed in the discussion and conclusions section (chapter 7) of this thesis.

2 Introduction to Heating and Cooling Systems in Commercial Buildings

2.1 Basic Functions

In applications for heating and cooling systems for large buildings typically a central unit for creating heat or cooling is combined with several smaller units for distribution of heat or cooling. Figure 1 below illustrates one example of how the heating and cooling is applied in an office building.

There are several methods for creating heating and cooling for commercial buildings; these methods can often be used either as single standing or integrated with various other solutions. Methods for heating and cooling systems include (but are not limited to) district heating and cooling, localized heating (district water only), geothermal heat pumps and water chillers. [7]

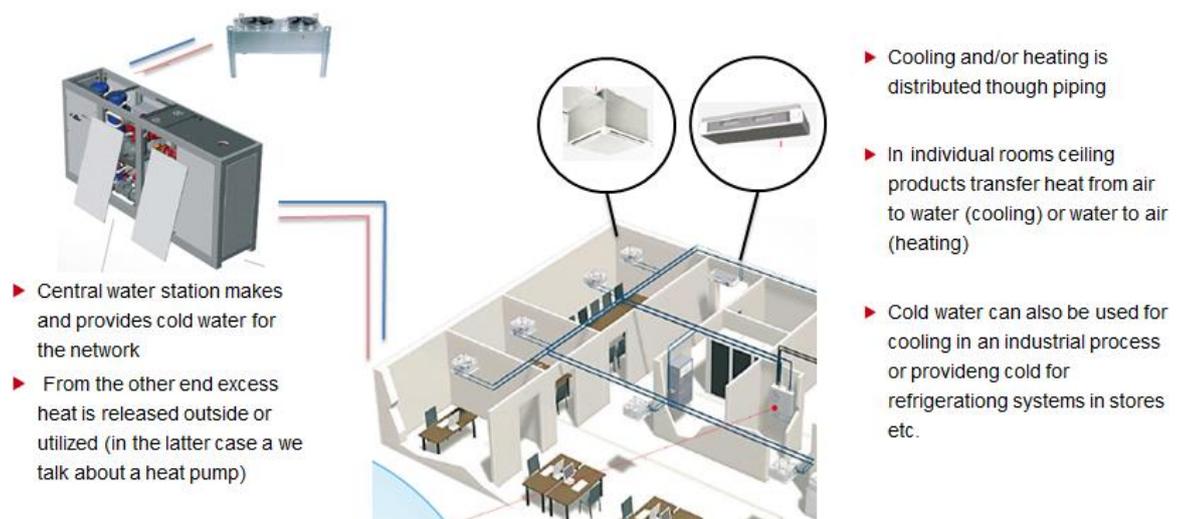


Figure 1. Example of a Cooling System in an Office Building. [7]

Since introducing different methods for providing heating and cooling for buildings would be a wide enough topic for a whole thesis, the reader is encouraged to search for additional reading if having no prior knowledge of these systems. Since this thesis is about heat pumps and water chillers it is assumed that either, or the combination of aforementioned for providing both heating and cooling, is used in the applications described in this thesis.

2.2 Process fluids

As mentioned above, a typical heating and cooling system involves four kinds of process fluids: refrigerant² (primary heat transfer fluid), water and/or coolant (secondary heat transfer fluid) and lubricant (oil). In applications where cooling is provided for a specific target only (for example server room) the cooled medium can be the air of the cooled space directly (other process fluid being coolant/refrigerant). [4] This thesis will concentrate on covering those applications where cooled and/or heated medium is water or water and glycol mixture; however, the sections covering coolant and lubricant are mostly directly applicable to direct air cooling and heating also.

2.2.1 Water

Water is used in heat pump applications for distributing the generated heat (or to absorb heat for cooling) throughout the system [8]. Figure 1 on page 3 shows how the water is distributed through the entire system and the cool/heated water is utilized in the ceiling units to cool/heat air of the individual sites.

Despite its various disadvantages mainly related to possible corrosion problems, water is the most common process fluid for heat distribution in commercial buildings since it is cheap and its thermal capacities are above most other fluids. Pure water is also harmless to both human and the environment, and its chemical properties can be quite easily alternated with various non-poisonous additives and water treatment methods to mitigate the negative effects that promote corrosion in aqueous conditions. However, whenever the heat transfer fluid is subjected to near freezing or below 0°C temperatures some type of antifreeze solution (see 2.2.2 Coolant) must be used instead of water to prevent damage to the system caused by freezing.

For water, the two most important indicators that should be monitored in order to be able set up optimal conditions for successful HACR operations are pH and water hardness; both are known to affect the corrosive properties of water. [9] Important indicators for water in HACR applications and their limit values are discussed into more detail later in this thesis.

² In Chiller R410A or R407C HCF refrigerants are used

2.2.2 Coolant

Although many types of antifreeze fluids or coolants are commercially available, glycol coolant is the one most often used as a secondary heat transfer fluid in HACR applications where the heat transfer fluid is exposed to below 0°C temperatures. Because of the higher initial cost of glycol as well as higher operation cost and decreased system efficiency, water and aqueous glycol solution can be used side by side in a HACR system: water circuit distributing heat and cooling indoors and glycol circuit for outdoor condensing cycle. In addition to lower thermal conductivities and heat capacities compared to water, glycols also have higher viscosities than water. Higher viscosity has a negative effect on pump performance and overall fluid flow. More power is needed of the pump in order to pump the more viscous glycol through the system. Because of the lower thermal conductivity the volumetric flow of glycol has to be greater in order to gain the same heating power as with water operated system. [4, 10]

There are two types of glycol commonly used for heating and cooling applications: ethylene glycol and propylene glycol. Ethylene glycol is more toxic and its usage should be avoided in food industry or whenever there is a possibility of a coolant leak to potable water [11]. However, in other applications than food and water industry, ethylene glycol is usually preferred due to its more superior thermal properties. Although both types of glycol have lower values for thermal conductivity and heat capacity than pure water, ethylene glycol has less negative effect on the overall system efficiency than propylene glycol [10].

Glycols are much more corrosive in nature than water. Corrosion inhibitors are added to glycols to mitigate their corrosive properties; when adequately formulated and maintained glycols can be considered as non-corrosive. Corrosion inhibitor levels and the overall condition of a glycol solution must be regularly monitored in order to prevent sudden and severe corrosion. [10, 11] Figure 2 below demonstrates the corrosive power of a non-inhibited 15% propylene glycol solution equivalent to about -4°C freeze protection.



Figure 2. Corrosive Power of Different Heat Transfer Fluids. [10]

Ethylene glycol is more corrosive than propylene glycol. Special care must be taken also in the selection of materials for a glycol system since glycol corrosion inhibitors do not provide full protection for all materials; for example aluminium and zinc are mostly unsuitable for glycol systems. Most manufacturers also have a limit for the minimum percentage of glycol in the solution that has to be reached in order to maintain proper functionality of corrosion inhibitors. [11]

2.2.3 Lubricant Oil

The main purpose of lubricant oil in the machinery is to reduce the negative effects of friction and wear arising from the contact of surfaces in the machine. Lubricant oils also cool the surface experiencing friction and prevent contamination of the surface by rinsing away possible particles. [12, 13]

Since lubricant oil has a mitigating effect on friction it also decreases operational costs and improves the life time of the machinery; in fact, most machines with moving parts would not function very long (or if all) without any kind of lubricant.

There are many kinds of lubricant oils commercially available. Lubricant oils can be mostly divided into two categories: mineral oils and synthetic oils. Mineral oils are pe-

petroleum (hydrocarbon) based oils whereas synthetic lubricants can be hydrocarbons, esters, silicones or polyglycols. [14]

Synthetic oils have overtaken petroleum based mineral oils in many fields despite their significantly higher initial cost. Synthetic oils have on average three times longer life-time than mineral oils, and in most cases they have better corrosion resistance, oxidative stability and thermal resistance than mineral oils [12, 14] In the Company synthetic mineral oils (polyol ester oils) and semisynthetic mineral oils are used depending on the type of machinery.

There are many kinds of synthetic oils commercially available on the market depending on the operating conditions of the machinery. Important variables for choosing the right synthetic lubricant include viscosity, materials compatibility, operation temperature of the machinery and corrosion protection. [14] For the Company, compressor oils are prefilled by the component manufacturers and maintenance oils are mostly supplied by the manufacturers directly.

3 Short Introduction to Corrosion and Wear in Heat Pumps and Water Chillers

3.1 Types of Corrosion

Most parts of water chillers and heat pumps are made of some kind of metal. Metals are typically used because of their high durability in wide temperature ranges and resistance to breaking and wearing as well as resistance to chemical reactions. However, metals have a tendency to oxidize in the presence of water or aqueous solutions. Rusting of iron is a typical example of corrosion in the presence of moisture and oxygen.

Different types of corrosion are generally grouped by the area of affection; when corrosion affects the entire inspected surface area it is called general corrosion (also referred as erosion corrosion). The other type is referred as localized corrosion; this type of corrosion usually affects only a small part of the inspected surface area but is harder to detect than general corrosion and usually leads to more rapid system failure. German Industry Standard DIN EN ISO 8044 defines corrosion as “the reaction of a metallic material to its environment, which effects measurable change in the material and

can lead to impairment of the function of a metal construction part or of an entire system [15]”.

Example images of both general and localized corrosion are presented in figure 3 below. The example image on the left hand side illustrates a special type of localized corrosion called pitting corrosion. Pitting occurs in conditions where the passive film of a metal has broken down, for example as a result of the presence of aggressive chloride ions. The dissolution of the passive film allows corrosion to take place and a pit is formed. Pitting is considered autocatalytic, i.e. once a pit is formed it creates conditions that will further promote the growth of the pit. [48]

It can be seen from the image that although the surface area affected by the corrosion on the left hand side image is large, corrosion has not made it through the surface of the pipe. On the right hand side image there is a clear hole in the pipe caused by pitting corrosion. Given that this pipe was installed in a HACR system and the pipe was filled with coolant solution, the presented corrosion damage would lead to coolant leakage and quite possibly to impairment of the whole system.



Figure 3. General Corrosion and Pitting Corrosion in a Copper Pipe [16, 17].

Cavitation is a special kind of localized corrosion that occurs in the presence of a liquid. Cavitation is formation of small voids in the liquid that is caused by sudden changes in the pressure near a solid surface. These voids in the liquid cause rapid implosions near the metal surface which in turn leads to pitting of the metal. [9] Figure 4 illustrates an example of cavitation corrosion on a phosphorous de-oxidized copper tube.



Figure 4. Cavitation on a Phosphorous Copper Pipe [18].

According to the source of the image, research done by the Leuven Catholic University Department of Metallurgy and Material Engineering, the time of failure in this case was two weeks after installation to an alcohol boiler unit [18]. The implosions of the cavitation voids have done severe pitting damage on the pipe leading to rapid failure of the pipe. As previously mentioned, pitting corrosion is hard to detect by any analysis of the process fluids since the surface area affected, and thus the amount of corrosion products, is fairly small. Cavitation and pitting corrosion are best prevented by careful product design and fluid condition monitoring. The mechanisms for cavitation are fairly well known, and with careful product design and fluid condition monitoring it is possible to avoid conditions that promote cavitation.

3.2 Scaling

Scaling is the formation of inverse-solubility salts on the surface of the equipment, for example on an evaporator or a heat exchanger. The most typical of these salts is calcium carbonate. Formation of scale on the surfaces of the heat exchanger highly reduces the efficiency of the heat exchanger. Since scale can be hard to remove, scaling can result to the need to change the heat exchanger; operation which can be costly and leads to system standstill while under maintenance.

Scaling and corrosion usually occur in the different ends of the pH spectrum; high possibility for scaling usually means low potential for corrosion and vice versa. However, aluminium has tendency to corrode under alkaline conditions resulting that aluminium heat exchangers can experience corrosion and scaling simultaneously. This can lead to significant reduction in the heat exchanger efficiency and to the impairment of the system. [19]

Scaling is typically a slow process that occurs over months or years. The existing calcium carbonate in a water solution can become insoluble for various reasons; the most typical being temperature increase, salt concentration increase and CO₂ loss from the solution. [49] Carbonate and bicarbonate salts exist in nearly all water resources. They can become dissolved in water through weathering of carbonate bearing rocks and dissolution of carbon dioxide from the soil or atmosphere. When carbon dioxide dissolves in water carbonic acid is formed. In aqueous solution carbonic acid further breaks down to carbonate and bicarbonate ions; the relative amounts of carbonic acid and carbonate and bicarbonate ions depend on the pH condition of the water resource. [50] With increasing temperature dissolved calcium reacts with bicarbonate forming insoluble calcium carbonate, and as side products carbon dioxide and water are formed. The aforementioned reaction is illustrated below.



Scaling is promoted in conditions where water hardness is high. According to an article *Water Chemistry Issues in Geothermal Heat Pump Systems* by Kevin D. Rafferty of American Society of Heating, Refrigerating and Air-Conditioning Engineers, scaling typically occurs when the water hardness exceeds 80 ppm (Calcium Carbonate hardness) and/or the pH is above 7.5 [20].

3.3 Corrosion and Metals

The most typical metals used in HACR applications are iron, steel alloys, copper and aluminium. Presence of different chemicals in the process liquids and chemical properties of the liquid, for example the pH value, promote the corrosion of metals used in the applications. Specific environmental factors such as low pH or presence of chloride ions affect different types of metals in different ways; some metals are more prone to undergo corrosion in certain conditions than others [9].

Corrosion due to material properties has to be taken into account already at the planning stage of a HACR system. Wrong combination of metals can lead to galvanic corrosion which occurs when two (or more) different kinds of metals are joined together in a way that an electrical circuit is completed. This enables the movement of the charged

particles making the less noble metal to undergo rapid corrosion whereas the corrosion rate of the more noble metal decreases. [21]

Although corrosion of iron is a very complex reaction involving many factors there are some general factors, such as low pH and the presence of oxygen, that promote the corrosion of iron and its alloys. In an open system the continuous presence of oxygen is likely to cause corrosion; however, in a closed system the oxygen is quite quickly consumed from water or glycol solution and will no longer pose a threat to the system [9]. Corrosion of iron can also take place under anaerobic conditions, especially in the presence of sulphate-reducing bacteria. Degradation of glycols through thermal oxidation produces organic acids which may further promote anaerobic corrosion. A study published in Solar Energy Materials journal states that thermal oxidation of glycols can occur with increasing temperature, the presence of metallic particles and under aeration and deaeration conditions; and that acidic degradation products are formed under all of these conditions [22]. Corrosion can also be promoted by other corrosive metabolites such as carbon dioxide and ammonia. [22, 23]

Without corrosion inhibitors iron and iron alloys tend to corrode already at neutral pH values; corrosion is accelerated increasingly the lower the pH value is. Communal water supply is controlled to be between 7 and 9, although small seasonal and areal deviations are possible [24]. This means that tap water as such can be corrosive to iron components in an HACR system, especially if other corrosive metabolites are present even in minor concentrations. Solid residue from cutting and welding of pipes can promote the corrosive potential of acidic water by eroding the passive film on the metal [9]. Solid iron residue arising from erosion corrosion can be found as dissolved or particulate iron in the water, or it can remain as scale on the surface of the pipe. This may lead to additional problems in the form of system blockage or decreased system efficiency (scale) and accelerated corrosion in the whole system (particulate iron). [9, 23]

Iron alloys such as stainless steel are more resistant to corrosion in similar conditions than cast iron; however the use of stainless steel in large applications is hardly ever cost-effective and single components such as joints, bends and valves can be 4-10 times (or even more) expensive compared to cast iron components (The Company purchasing database and calculation for costs).

While stainless steel is rather resistant to general corrosion, pitting corrosion can present a problem in certain conditions. A study by Asaduzzaman et al. from University of Rajshahi states that the presence of chloride in ionic form promotes localized breaking of the passive film of the steel causing possibly severe pitting corrosion. When the studied Commercial grade AISI-304L austenitic stainless steel rods were immersed in sodium chloride solutions having the concentration of 3.5% or higher of NaCl pitting was heavily accelerated after a short period of time. [25] It is not unusual to seawater to have NaCl concentration of 3.5% or over which means special attention has to be paid on the possible pitting problems of stainless steel in seawater applications.

Dealloying or selective leaching is a form of corrosion in which a specific component of an alloy is subjected to corrosion while the other components remain relatively intact. Some alloys, for example brass, are more prone to dealloying than others. In dealloying of brass zinc dissolves leaving behind a weak and porous copper structure. The selective leaching of brass and steel is promoted in chloridic and stagnant water conditions. [26]

Copper and brass are more resistant to corrosion than aluminium and iron. As mentioned above, selective leaching can present a threat to brass components under certain conditions. Example images of dealloying of brass (dezincification) are presented in figure 5 below. From the image of the hose tail (left) it can be seen that almost all of the zinc has been dissolved leaving the remaining copper structure extremely brittle and susceptible of breaking from even the smallest tap or twist. On the right hand side image the reddish inner circle of the fitting is the depth to which dezincification has proceeded prior to the removal of the fitting. According to the source of the image this fitting was installed in a seawater application for five years. [27]



Figure 5. Dezincification on a Brass Hose Tail (left) and Brass Fitting (right). [27]

In aqueous conditions a protective layer is formed on the metal surface of the copper. This protective layer consists mainly of copper oxides and carbonites. Stagnant water conditions early after component installation may prevent the formation of these protective layers allowing corrosion to take place. Since both too high pH (> 8.5) and too low pH (< 6.5) promote corrosion of copper components, the water quality should be carefully monitored before (and during) the use in HACR application. [29]

In addition to steels, also aluminium has the tendency to experience pitting corrosion in the presence of ionic chloride [9]. In an HACR application aluminium is typically used in heat exchangers. Pitting in heat exchangers leads to decreased efficiency of the system, and eventually to system standstill since the corroded heat exchanger needs to be replaced; an operation which is both costly and time consuming. Epoxy and hydrophilic coated aluminium is often used in heat exchanger fins to extend the fin life in aqueous and acidic conditions [29].

Pitting corrosion in an aluminium fin can occur prior to the installation if the coils have not been properly dried after the manufacturing process or they have been exposed to unfavourable conditions during the transport or warehousing. Pitting in an aluminium fin can be hard to detect and can even pass initial testing in manufacturing phase; or sometimes even end up installed in applications. Depending on the size and location of the initial pit, problems may arise in weeks, years or sometimes never.

4 Corrosion and Process State Indicators in Heat Pump and Water Chiller Process Fluids

While there are almost infinitely many indicators for process fluids with which to detect and foresee possible system dysfunctions, it is important to remember that no one indicator or one-time test can give reliable information of the overall system condition. Thus the correct interpretation of the test results is as (or even more) important than the results themselves. Finding the tests and indicators that best describe the overall condition of the machinery and process fluid is hard since one often wants to limit the amount of tests for economic reasons. In this chapter the most common indicators and their alarm limits are discussed; the reader is advised to take notice that there are various possible tests, and indicators, which exist that are not described in this thesis.

As important as choosing the most descriptive tests are choosing the correct sampling methods and time intervals. These methods and time intervals are discussed in the next chapter of this thesis.

4.1 Choosing Indicators and Setting Alarm Limits

Choosing the indicators for best coverage and setting up alarm limits can be a tedious job even if one is very familiar with the machinery in question. The best results would be gotten from analysis specifically designed for the type of machine; however, designing and implementing various analyses is often too costly and time consuming, and reliable enough results can be obtained by generic analysis [30].

Before adequate alarm limits can be set, one should know the baseline for the tested fluid, that is, the values for the parameters to be tested at point zero operation. In cases where the baseline properties for the fluids are not provided by the manufacturer the user should conduct the baseline tests prior to use in any application. For communal water resources the baseline parameter values can often be gotten from the supplier; according to current legislation in Finland the supplier is obliged to keep track of the most common water parameters, i.e. pH, TDS³, BOD⁴ et cetera [31]. However, the aforementioned data might only be publicly available months afterwards, and, in case of any sudden situation with the supplier, (for example leakage from the sewage sys-

³ Total Dissolved Solids

⁴ Biological Oxygen Demand

tem to potable water, flooding etc.) might not even be accurate (many parameters are monitored offline for example once or twice a day). Thus it is recommended to test the quality of the water at the point of installation.

When dealing with old installations however, it is not often possible to determine the baseline values for the parameters. For example in case of lubricant oil it can be that lubricant oils from various different manufacturers have been added to the machine during the years of operation. In these cases, given that the condition of the process fluid is still within operation limits, a new baseline can be set according to the current situation in order to be able to detect future trends. If, however, the test parameters of the process fluid would fall far beyond the general alarm limits, it would be recommended to change the process fluid and set a new baseline accordingly. If one would continue to use the same process fluid, it is more than likely that any trends or signs of possible problem would not be detected in time.

Optimistically, the parameters tested would be those that best describe the overall condition of the process fluid with the least amount of tests. Various researches covering these parameters in HVAC applications have been made, and the parameters chosen in this thesis are the ones most commonly agreed upon as mandatory. In the Company, systematic and preventive process fluid testing is not yet a common procedure and thus it can be assumed that the test parameters will be adjusted in the future when more experience and data is gathered.

According to literature there are three common alarm types to be used in process fluid analysis: statistical, absolute and percentage based alarms. Statistical alarms are used for identifying machine wear related problems over time. Absolute and percentage alarms are used for monitoring the current condition and health of the process fluid as well as process fluid contamination and degradation levels. [32, 33, 34, 35] Furthermore, it is not only important to set specific limit and alarm values for upper and lower values of a certain indicators; it is as important to monitor and set alarm limits to the rates with which these parameters change [32].

Statistical data analysis techniques and tools, such as CUSUM⁵ and CDA⁶ are a more advanced way of analyzing data and detecting possible trends in process fluid monitor-

⁵ Cumulative Sum of Errors

⁶ Change Detection Algorithm

ing data. However, these techniques can be reliably applied only when the number of data points is fairly large, i.e. on-line monitoring. Acquisition of enough data points in an off-line monitored process would be tedious and time consuming, and would not be likely to give the wanted outcome. [33, 42]

For the Company's equipment monitoring and reporting purposes I decided to apply a so called "traffic light system". A parameter that exceeds the initial alarm limit would turn the traffic light yellow and recommendations for more frequent monitoring would be given. A parameter testing above a set critical limit would turn the lights red (see Appendix 1: Reporting Template for Oil Analysis) and recommendations for maintenance actions should be given. At this point of initialization of the monitoring and reporting system no system for monitoring the rates of change of tested parameters has yet been developed. For effectively monitoring and analyzing the rates of changes more data needs to be collected.

4.2 Fluid Condition and System Dysfunction Indicators and Their Limit Values for Lubricant Oil

Various researches indicate that the most important indicators for lubricant oil condition are wear metals, particle count, moisture content and acid contamination (TAN/AN⁷) [2, 30, 32, 35, 36, 37, 38]. Other sources suggest also viscosity, degree of oxidation, dielectric constant and pH to be amongst the important indicators, while others discuss the necessity of moisture content monitoring [39, 40, 41].

In the article *Extending Lubricant Life* the author, David Withby, suggests that acidity of the oil can be used as a measure for the progress of oxidation [39]. It is known that moisture content in oil can lead to increase in acidity of the oil and therefore it would be enough to monitor only the acidity level; however, after reading multiple studies I decided to keep the moisture content as an important indicator since it also gives vital information of the original condition and degradation rate of the oil.

⁷ Total Acid Number/Acid number

The Clean Oil guide by [C.C.Jensen A/S, 2011], amongst various other sources, recommends that for mineral based oil the moisture content should not be more than 100 ppm for optimum performance [2, 12]. However, experience has shown that even new oil from the manufacturer often exceeds this limit (data based on samples from the Company), and no evidence has been detected that water level this low would lead to machine failure or dysfunction. Maintaining such low limit value would lead to most samples not passing the test satisfactorily, which in turn would lead to unnecessary oil changes and added maintenance costs. Most literature sources seem to agree 500 ppm to be the critical limit for moisture content in oil [30, 39]. However, most manufacturer oil analysis and ready oils analysis kits state the water content only as being below or above 0.1% (1000 ppm) [2, Company's requests for quotations for oil analysis]; which according to the literature is not exact enough for reliably detecting possible problems nor it would be accurate enough to detect any trends, i.e. degradation of oil with rising moisture content.

For the Company's purposes initial alarm limit of XX ppm was chosen. Oil being tested for under XX ppm moisture content would keep the "traffic light" green, whereas oil with moisture content between XX-XY ppm would turn the light yellow. For moisture contents above 500 ppm the traffic lights would turn red.

According to literature, two main reasons for compressor failures are particle contamination of oil and liquid refrigerant flood back [38, 43]. A study by M.R Sari, F. Ville, A. Haiahen and L. Flamand suggests that solid particles sizes 40 μm and smaller can increase the friction coefficient significantly and have a significant effect on equipment wear by fatigue or adhesion [38]. The Clean Oil Guide [2] states that the particles with similar size or bigger than the dynamic tolerance between the moving parts in the oil system have the most detrimental effect on the system, that is, particle size 1 to 5 μm or bigger. The ISO 4406/1999 and ISO 4407/1999 coding for particle contamination in oil use particle counting in sizes 4/6/14 μm and 2/5/15 μm respectively. ISO cleanliness levels according to the particle count are presented in figure 6 on the next page.

ISO Code	Description	Suitable for	Dirt/year
ISO 14/12/10	Very clean oil	All oil systems	8.5 kg *
ISO 16/14/11	Clean oil	Servo & high pressure hydraulics	17 kg *
ISO 17/15/12	Light contaminated oil	Standard hydraulic & lube oil systems	34 kg *
ISO 19/17/14	New oil	Medium to low pressure systems	140 kg *
ISO 22/20/17	Very contaminated oil	Not suitable for oil systems	> 589 kg *

Figure 14: Contamination guide for hydraulic and lube oil systems

ISO Code	Description	Suitable for	Improvement factor	Dirt/year
ISO 14/12/10	Very clean oil	All oil systems	200%	8.5 kg *
ISO 16/14/11	Clean oil	Critical gear systems	150%	17 kg *
ISO 17/15/12	Light contaminated oil	Standard gear systems	100%	34 kg *
ISO 19/17/14	New oil	Non critical gear systems	75 %	140 kg *
ISO 22/20/17	Very contaminated oil	Not suitable for gear systems	50%	> 589 kg *

Figure 6. Contamination Guide for Oil Systems According to ISO classification. [2]

In addition to particle count the concentrations of the most common wear metals (Al, Cr, Cu, Fe, Mo, Ni, Pb, Sn), oil additives (B, Ba, Ca, P, Zn) and contaminants (K, Li, Na, Si; coolant leakage indicators) should be monitored. Rather than setting up specific limits for these substances it is more important to monitor the rate at which the concentrations of these metals are changing [2, 38, 41]. Sudden increases in concentrations and abundance rates would most likely indicate rapid corrosion or coolant leakage. An article by Mike Johnson and Matt Spurlock published in Tribology & Lubrication Technology 2009 suggest that a 25% increase in the metal levels should be considered alerting [30].

Acidity and viscosity are parameters to which assigning an alarm point is hard or almost impossible without the knowledge of the new oil properties. Most literature sources seem to agree that +1 increase in TAN over the baseline sample is the critical limit for any oil; and that +0.5 rise in TAN over the baseline sample should be considered alerting. [2, 30].

A general rule for viscosity for lubrication oils in industrial applications is that a change of 5% in the viscosity of the oil over or under the baseline sample should be considered alarming, and that with changes more than +/-10% immediate actions should be taken. [30]

In sampling stage the visual inspection of an oil sample is also important. New lubricant oil is bright, relatively colourless and has no solid material. Black colour of the oil is a tell-tale sign of too high operation temperature; cloudiness of the oil or solid material indicates to contamination or undissolved additives in the oil [2, 30, 44]. A support sheet for visual inspection the Company's maintenance personnel can be found in appendix 2.

4.3 Corrosion Indicators in HACR Process Water

As mentioned in Chapter 2.2.1 of this thesis, pH and water hardness are the two most important indicators for water used in HACR applications. [9] In order to prevent metal corrosion pH should be maintained slightly on the basic side (pH 8-9) [24]. According to a study by Kevin D. Rafferty published in ASHRAE journal, water hardness above 80 ppm can cause serious scaling issues in heat pump systems [20]. Since water hardness in Finland can vary between 50 ppm to 320 ppm [24], water quality testing prior to application is advisable. In case of poor water quality from communal water supplier local water treatment engineer should be consulted.

According to the Handbook of Heat Exchanger Fouling chlorine concentration in heat exchanger applications over 0.5 mg/l is likely to promote corrosion problems [51]. The Heat Exchanger Care and Water Quality Guide by MTS Systems Corporation suggests a limit of 5 ppm for chloride concentration ion heat exchanger applications [52]. Since the limit for chlorine concentration recommended is significantly lower than the upper limit value for communal water supplies set by the Ministry of Social Affairs and Health, more research into the issue will be needed.

The limits set by the Ministry of Social Affairs and Health for communal water supplies are presented in figure 7 below. Figure 8 presents the limit values for common compounds in cooling water supplies according to the Heat Exchanger Care and Water Quality Handbook.

	<u>Raja-arvo</u>		<u>Tavoitetaso</u>
MIKROBIOLOGISET LAATUVAATIMUKSET			
<i>Escherichia coli</i>	0 pmy/100 ml		
Enterokokit	0 pmy/100 ml		
KEMIALLISET LAATUVAATIMUKSET			
Akryyliamidi	0,10 µg/l	LAATUSUOSITUKSET	
Antimoni	5,0 µg/l	Alumiini	200 µg/l
Arseeni	10 µg/l	Ammonium	0,50 mg/l
Bentseeni	1,0 µg/l	Kloridi	250 mg/l
Bentso(a)pyreeni	0,010 µg/l	Mangaani	50 µg/l
Boori	1,0 mg/l	Rauta	200 µg/l
Bromaatti	10 µg/l	Sulfaatti	250 mg/l
Kadmium	5,0 µg/l	Natrium	200 mg/l
Kromi	50 µg/l	Hapettavuus	5,0 mg/l
Kupari	2,0 mg/l	<i>Clostridium perfringens</i>	0 pmy/100 ml
Syanidit	50 µg/l	Koliformiset bakteerit	0 pmy/100 ml
1,2-dikloorietaani	3,0 µg/l	Pesäkkeiden lukumäärä	1)
Epikloorihydrini	0,10 µg/l	pH	6,5 - 9,5
Fluoridi	1,5 mg/l	Sähkönjohtavuus	< 2 500 µS/cm
Lyijy	10 µg/l	Haju	2)
Elohopea	1,0 µg/l	Maku	2)
Nikkeli	20 µg/l	Sameus	2)
Nitraatti	50 mg/l	Väri	2)
Nitriitti	0,5 mg/l	Organisen hiilen kokonaismäärä	1)
Torjunta-aineet	0,10 µg/l		
Torjunta-aineet yhteensä	0,50 µg/l		
Polysykliset aromaattiset hiilivedyt	0,10 µg/l		
Seleenit	10 µg/l		
Tetra- ja trikloorieteeni yhteensä	10 µg/l		
Trihalometaanit yhteensä	100 µg/l		
Vinyylkloridi	0,50 µg/l		
Kloorifenolit yhteensä	10 µg/l		

Figure 7. Quality Demands Statute 461/2000 on Communal Water Supplies by the Ministry of Social Affairs and Health [24]

Water Chemistry

Compounds found in water	Allowable quantity (parts per million)
Ammonia	none
Bacteria	must be bacteriologically safe
Calcium	<800 ppm
Chlorides	<5 ppm
Dissolved solids	>50 but <500 ppm; limit to 150 ppm if abrasive solids present
Iron	3 ppm
Nitrates	<10 ppm
Nitrogen compounds	none
Oxidizing salts or acids	none
pH level	6–8.5 recommended
Silica as SiO₂	<150 ppm to limit silica scale
Sulfides	<1 ppm
Sulfur dioxide	<50 ppm

Figure 8. Water Chemistry Limit Values for Water Supplies in Cooling Water Applications [52]

For water samples visual inspection is as, or even more, important than for oil samples. Clean water is a colorless and odorless liquid that does not contain any visible solids. In case of the sample failing visual test additional tests, based on the visual inspection results, should be assigned for the sample. Appendix 3 illustrates an example report of water and coolant analyses for Company's customers.

4.4 Coolant Condition and Corrosion Indicators

According to literature sources the pH of glycol solution should be maintained slightly on the basic side, between 8-10, to avoid corrosion and minimize glycol degradation [11, 22, 45]. Besides for pH, glycol solutions should be tested for antifreeze properties and additive concentration [22]. It is recommended not to use glycol concentrations higher than 50% for propylene glycol and higher than 40% for ethylene glycol in order to maintain optimal heat transfer conditions. Various instant test kits measuring the antifreeze properties and additive levels in glycol are commercially available and in most cases these are reliable enough not to need any additional laboratory testing. However, in case the visual inspection of glycol solution should reveal anything out of order, for example change of colour or solids, the sample should be sent for further testing. Solid material in the glycol solution can indicate corrosion of the system.

All process fluids should be at least visually inspected quite soon after the installation; sometimes solids from welding and cutting of the piping can remain in the pipes and bends. To minimize the possible problems and to avoid costly reclamations and maintenance procedures this initial sampling point is highly advisable. The aforementioned solid machining residues can cause severe system problems in the future, and the origin will be hard to pinpoint after years of usage.

5 Process Fluid Sampling

For effective and accurate analysing correct sampling methods are as important as the adequate analyses of the samples. From a wrong sampling location one can get completely misleading results and thus end up with inaccurate conclusions which can lead to costly and unnecessary maintenance procedures [2, 46].

There are three key parameters in a well-designed sampling system: timeliness, representation accuracy of the actual conditions, and repeatability [47]. Equipment run hours for all equipment should always be carefully monitored and documented prior to sampling. Also any unusual activity (maintenance breaks, system shutdowns et cetera) should always be documented in order to be able to effectively draw conclusions from the analysis results.

Many literature sources recommend monthly or even weekly monitoring for sensitive equipment [2, 32, 37, 47]. However, maintaining such dense sampling would be costly and thus extremely hard to sell to the end customer. After consulting various studies (see list of references no 2, 5, 13, 30, 32, 33, 37, 38 and 43), I came to a conclusion that sampling interval of 3-6 months should be adequate for the Company's purposes. Six months intervals could initially be recommended for new equipment and for equipment which initial analyses would pass as good (green light in the "traffic light" system, see chapter 4.1). Quarterly (or even denser) intervals could be assigned to equipment with any alarming analysis results. It should be noted that in most cases even in the case of alarming analysis results there is no need to reanalyze all of the parameters; monitoring those with the exceeded alarm limits (and parameters closely related) would likely be sufficient.

The key to a successful sample is to take the sample from a location that best represents the fluid condition in the overall system. Samples should be taken from a location with high turbulence, optimistically from a bend or upwards pointing pipe. Sampling location should be on the end of the fluid line but before any filters or fluid reservoirs [2, 46, 47]. If all of the aforementioned conditions cannot be met, the possible interference with sample quality should be taken into account in the analysis. Figure 9 illustrates the best sampling point, i.e. a bend on the end of a fluid line (high turbulence area) (left) and return on a drain line prior to fluid reservoir (right).

Expert articles emphasize the necessity of fixed sampling ports for high quality samples; as previously discussed this is hardly possible with the old equipment. However, it is recommended to consider the possible installation of fixed sample ports in the new equipment.



Figure 1. Highly Turbulent Area

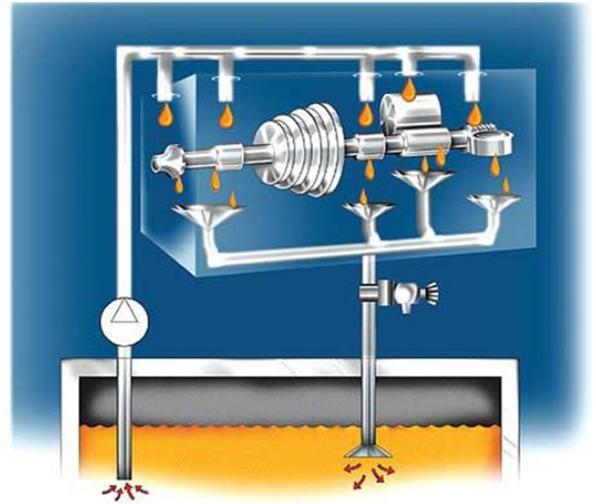


Figure 2. Return or Drain Line

Figure 9. Optimal Sampling Location for Oil Samples. [46]

Since the installation of fixed sample valves and ports to old equipment would be extremely difficult, the correct sampling location of old equipment should be confirmed from the head of maintenance and product engineer according to the guidelines presented in this thesis prior to any initial samples. It should be noted that to ensure repeatability the sampling location should always remain the same for any individual equipment [47].

Detailed instructions on sampling from different locations can be found online and these instructions should be consulted in case of uncertainty. For example the webpage for Machinery Lubrication Journal offers detailed sampling instructions at www.machinerylubrication.com.

According to literature review and answers from laboratories to the Company's requests for quotations concerning process fluid analyses, samples should be gathered to hard plastic bottles with minimum 250 ml volume. For water and glycol samples also a smaller volume would be sufficient, but for clarity and logistical reasons it is easier to use only one size of sample bottles. To ease out sampling procedure for the Company's maintenance personnel, ready sampling kits containing the necessary equipment, i.e. plastic bottle, water quality strips, sample label stickers, sample template and instructions for sampling were made. Example sampling kit is presented in figure 10 (example sample kit for oil sample, water quality test strips not included). The material of the sampling bottle chosen is HDPE.

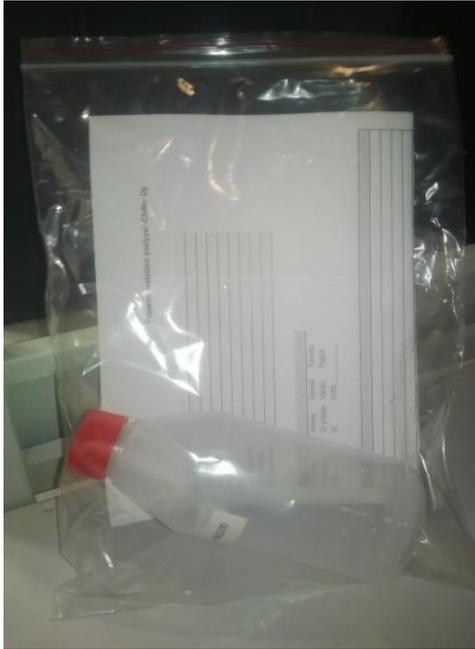


Figure 10. Example Sampling Kit for Oil Samples.

Prior to collection it is important to drain the sampled fluid at least 2 times the sample volume (in this case 500 ml) [2, 47]. Sometimes extensive flushing of the sampled fluid is not possible, for example when obtaining sample from a compressor. In these cases one should flush/drain the sampled fluid as much as possible before collecting the sample.

6 Economics of Process Fluid Analysis

It is clear that the introduction of systematic process fluid sampling process will introduce major savings in maintenance procedures and reclamation cases. The initial costs for launching the service are fairly small since the Company already offers extensive and systematic maintenance services to its customers, and most of the necessary research has already been done while writing this thesis. The training of the personnel is estimated to take maximum of 2 hours and assembling the training material should not take more than 6 man hours. Additional short individual training sessions might be needed during the initialization and launching period.

As discussed in the previous chapter, obtaining the suitable price point for the oil analysis has proven to be rather difficult. The current price point varies around ZZ to ZY €/sample range, while around YX-XY € would be the maximum with which the service could be sold to customers [Company's requests for quotations]. Additional requests for quotations for laboratories located in Europe will be sent during the summer and early autumn of 2015. In the initialization stage the profit margin is expected to remain rather small, but after successfully launching the service and after a suitable partner laboratory for the analysis has been found the profit margin should increase. It should be noted that in addition to profit the reliability of the maintenance services offered by the Company increases in value for the customers.

The main costs related to standard water and glycol tests will arise from the time used for sampling and analysis. However, should any alarming test results from the standard tests be gotten, the costs for the additional tests should be considered on a case-by-case basis. Quotations for some standard type analysis (for example wear metal, organics) should be gotten from the laboratories prior to launching of the service in order to alleviate the service pricing for the customers.

7 Discussion and Conclusions

During this thesis process fluid condition indicators and alarm limits for those indicators were set. Since the service of providing process fluid monitoring for the Company's customers is still in the initialization stage it can be assumed that the indicators and/or alarm limits are likely to be adjusted in the future as more experience and data is gathered. Continuous development will be applied to the service after the launching stage,

and more scientific approaches and tools for data analysis will be considered for application in the future.

As there are no prior experience or literature sources concerning process fluid condition monitoring and analysis in the exact type of equipment that the Company manufactures, some adjusting through trial and error might be needed in setting of proper intervals for the sampling. In order to gain more information while keeping the customers satisfied it is recommended that denser sampling interval would be maintained in the beginning of the launching period, even if it means smaller profit margins initially. In order to be able to provide the best possible service for the customers few pilot companies should be recruited prior to launching of the service to all customer companies. By piloting before the big launch it should be able avoid or detect any possible major setbacks of the system.

Since the analyses chosen for the process indicators are rather standard in the area of business, it is not likely to expect any major setbacks or difficulties in the analysis methods; rather the possible problems are to lie in the setting of the sampling intervals as previously mentioned. Some difficulties should be expected in the initialization stage of the service concerning the analyses for old equipment where no process fluid analysis has been applied in the past. It is also advisable to familiarize the customer of the mitigated reliability of these initial analyses. Once few data points, i.e. 4-8 samplings during the period of 1-2 years including heavy load and low load seasons as well as maintenance breaks, have been successfully gathered from old equipment, the reliability of the analysis is assumed to rise to the same level than with new equipment.

For this extent of service successful launching period of 2-3 years can be expected. Setting up the client basis as well as adjusting the sampling and analysis will be likely to take a couple of years before the profit margin can be optimized. During the launching period continuous training of personnel is advised. Also 2 to 3 persons within the company should be trained for analyzing the results gotten from the laboratory and instant test results and for customer reporting.

As previously mentioned, the initialization period and quotations analysis will take place during the summer and early autumn in 2015. Launching period and adjustment and data gathering period is planned to take place during the late 2015 until 2017, by which

is assumed that enough experience is obtained for systematically operated and running service.

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