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Removal of Grease from Wind Turbine Bearings by Supercritical Carbon Dioxide

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This work aims to test the ability of liquid carbon dioxide to remove grease from bearings in wind turbines. Currently, the removal of grease from wind turbines offshore in the North Sea is done by dismantling the bearing covers and scraping off the grease. This procedure is long, labour intensive and raises maintenance cost. Another issue is the environmental policy, the approval for newly introduced chemicals for flushing purposes are procedurally long. If the problems with grease removal could be solved in a different way other than manual removal or using chemicals, it will open many new market opportunities and would carved out a niche for the wind turbine maintenance industry. The solution of flushing grease could lower cost, time and reduce environmental impact by applying Supercritical Carbon Dioxide. The oil based grease SKF LGWM 1 was designed to handle extreme pressure and low temperature conditions. The grease covered the main bearing for 4 - 5 y in a wind turbine at Horns Rev 1 Offshore Wind Farm in the North Sea, 14 km from the west coast of Denmark. The series of experiments focused on higher pressures and temperatures as well as the use of some co-solvents. The highest recovery by pure carbon dioxide is 26 % and was achieved at 60 MPa and 80 ˚C while the addition of Kirasol-318SC improved the recovery by 8 % at the same conditions. Outgassing losses increase with the addition of kirasol. The low recoveries and high pressures obtained by the experiment do not provide an applicable method for grease removal; however it can be implemented for the removal of the contaminants from grease wastes.

1. Introduction

1.1 Wind turbine industry development

The wind turbine industry is rapidly increasing around the world. According to the GWEC (Global Wind Energy Council) by the end of 2011 there were 199,064 wind turbines in operation. Based on the GWEO's (Global Wind Energy Outlook, 2012) moderate forecast, it is expected that a total accumulated installation of 759 GW could be reached by 2020, an annual market growth of 100 GW during the 2020's and by 2030 an accumulated installation of 1,600 GW. The total accumulated amount of 1,600 GW is equivalent to 228,571 Vestas V164 - 7.0 MW wind turbines. Vestas V164 - 7.0 MW is the largest offshore wind turbine and tests are being conducted offshore from Frederikshavn, Denmark (2013). Denmark being the pioneer in this sector has showed an increase in research and development from new materials to installation of wind turbines offshore; including Operations and Maintenance (OM) which is the aim of this paper.
Several oil and gas service, supply or related companies are including wind energy in their portfolios, knowing the current and future potential of the industry. "Most offshore wind turbines are produced in and shipped from Denmark, and it is estimated that Danish companies have been involved in 90 percent of all offshore wind projects in Europe" (Offshore Center Denmark, 2012), with an annual growth between 30 to 40 %. Some expect that the offshore will take over the onshore wind turbine installations because the licensing and noise regulations are simpler, as well as steadier wind conditions for electricity generation. There are different advantages and disadvantages offshore. In terms of commissioning, operations and maintenance costs are higher but offshore wind turbines can be larger and because of the wind conditions produce more energy compared to onshore. Another factor is that offshore wind turbines may last longer because of the lower turbulence at sea which reduces some maintenance costs.

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A wind turbine is expected to last approximately 20 y with a workload of 120,000 h; which is equivalent to ~66 % of their lifespan. “Maintenance costs are low but as the wind turbine ages the costs will increase”. “New generation wind turbines have lower maintenance costs”. Older wind turbines have an annual maintenance cost of ~3 % of the original investment compared to new generation which are larger, more efficient and with costs between 1.5 to 2 % (Wind Measurement International). Maintenance costs have a fixed annual amount or sometimes it is preferred to base maintenance cost on annual power output or kWh. A theoretical approach can also be applied based on pre-posterior Bayesian decision theory described in Sørensen (2009), who takes into account the uncertainty related to deterioration of the equipment and future costs related to inspection/monitoring, maintenance, repair and failure.

1.2 Bearings and lubrication

According to research, a grease producer and Danish companies no flushing system has been developed for the removal of grease from bearings. Vacuum flushing systems exist but only for oil removal from the gearbox, generator and other components. Grease pumping systems exist and based on field test it can reduce the time spent on lubricating the equipment at least by 50 %. It could be expected that a fully operational flushing system could save up to the same maintenance time.

The section of the wind turbine that wears out faster is the rotor blades and the gearboxes; mainly affected by lifetime, turbulence, air density, salinity, humidity, among others (Turi and Marks, 2010). Total energy output can be reduced to 10 % because of equipment failure. Out of that 10 %, approximately 5% is the inability of the gearbox to function and the most common cause is bearing failure.

Bearings are part of the machine elements together with the shafts, couplings, gears, dampers, fastening and joining. “Bearings are used to reduce frictional resistance between two surfaces undergoing relative motion. They are found in main shaft mounting, gearboxes, generators, yaw systems, blade pitch systems, and teetering mechanisms to name just a few”. “For any high-speed applications, ball bearings, roller bearings, or tapered roller bearing may be used” (Manwell et al., 2009). In the wind turbine industry ball and roller bearings are widely used and made of steel or composites depending on the design.The roller main bearing is shown in Figure 1. Both types consist of an inner ring, outer ring, the cage and balls or rollers. The bearings grease cover approximately 35 to 40 % of the bearings volume to reduce friction. The amount to be applied depends on the company design and function of the bearing. The friction in the bearing increases rapidly when the wind turbine starts rotating, requiring a high performance lubricant which in this case is grease. A research paper was published by Katz (2010) using data from Antriebstechnik, where he mentions the causes and distribution of bearings failures. Based on the analyzed data only 0.35 % of all rolling bearings do no reach their expected lifetime, 80 % of the causes are related to the lubricant and contamination factors, the rest by unsuitable choice of bearings (10 %), secondary damage (5 %), mounting faults (4 %) and defects caused by materials or production (1 %). The major causes summing the 80 % are the following: 20 % unsuitable lubricant, 20 % aged lubricant, 15 % insufficient lubricant, 20 % solid contaminants and 5 % liquid (Katz, 2010). Knowing that the lubricant is a major cause of bearing failure, which will affect the gearbox and in the long-term could reduce by ~5 % the total generation output it becomes an ideal topic for research and development.

The grease obtained for experimental purposes SKF LGWM 1 can be found in the main bearing as shown in Figure 1, located at the front of the wind turbine. The grease covered the main bearing for 4 - 5 y in a wind turbine at Horns Rev 1 Offshore Wind Farm in the North Sea, 14 km from the west coast of Denmark. A large range of different ISO-VG (viscosity grades for industrial lubricants) exists depending on the equipment, temperature, pressure and conditions. Based on Mobil Industrial Lubricants main bearings require a lubricant that can handle - 30 ˚C to + 70 ˚C, pitch and yaw bearings between – 30 ˚C to + 50 ˚C and the generator – 30 ˚C to + 100 ˚C. Mobil suggests the use of ISO-VG 460 grease for the main, pitch and yaw bearings, while for the generator usually a lower viscosity grease (ISO-VG 100) (Errichello et al., 2010). SKF recommends two types of greases for main bearings: LGWM 1 for extreme pressure and low temperature bearings and LGWM 2 for high load and with a wider temperature range. LGBB 2 for the blade and yaw bearings. For these SKF greases no specific ISO-VG is described in the safety data sheets.

2. Materials and Methods

The semisolid solute used for the experiments is grease produced by SKF, named LGWM 1. The grease was supplied for experimental purposes by Ocean Team Scandinavia A/S, Esbjerg, Denmark. The grease is a low mineral oil based with lithium soap acting as a thickener, with a viscosity index of 95, brown color observed before applied in the wind turbine bearing after a period of 4 - 5 y it has a dark brown-blackish color. The grease has a non-Newtonian effect and an oil film formation occurs at low temperatures down to - 30 ˚C, expected operating temperatures can range from - 30 ˚C to + 110 ˚C, having good pumping characteristics at low temperatures, with good corrosion protection and water resistance. The base oil viscosity of the grease at 40 ˚C is 200 mm^2/s and at 100 ˚C is 16 mm^2/s, flash point >150 ˚C and a density <1 g/cm^3 at 20 ˚C. A sample of the grease was heated and measured to observe any physical changes: 22 ˚C to 72 ˚C no drastic change, 90 ˚C and 100 ˚C the grease began changing from a semisolid to liquid form, and between 110 ˚C and 120 ˚C the grease started gasifying in large amounts.

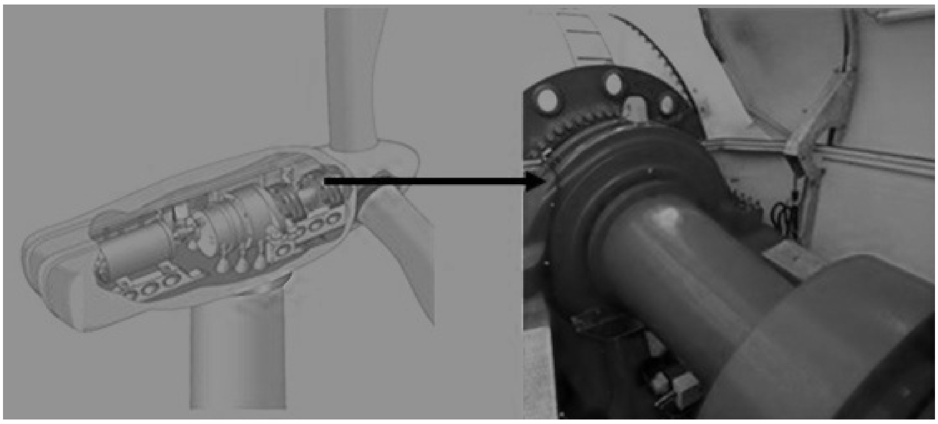

Figure 1: Wind Turbine Main Bearing (Reproduced with permission of: SKF Denmark A/S)

The solvent used is 99.9 % pure carbon dioxide, and was supplied for experimental purposes by Strandmøllen A/S, Denmark.
The co-solvent is Kirasol-318SC produced by Euro Corpex Limited, Great Britain. Distributed by Nordic Chemical Solutions A/S, Norway and supplied for experimental purposes by Ocean Team Scandinavia A/S, Esbjerg, Denmark. Euro Corpex describes Kirasol-318SC as exceptionally effective heavy duty, low foam industrial cleaner and oil emulsifier concentrate that removes grime, oils, greases, light hydrocarbons and entrapped contaminants. It loosens and disperses entrapped contaminants preventing their redeposition and enabling them to be easily washed or wiped away. Kirasol-318SC safety data sheet describes the boiling point to be at 100 ˚C 1013 hPa, flash point >100 ˚C with a density between 1.01 to 1.11 g/cm^3 at 20 ˚C.

3. Experimental

The experiments were carried out in the Chemistry Laboratory at Aalborg University Esbjerg, Denmark. Three materials were used throughout the experiments: a semisolid solute (grease), a solvent (CO_2) and depending on the experiment a co-solvent (Kirasol-318SC). Three types of experiments were conducted using carbon dioxide and grease: first type of experiment at moderate pressure and temperature, second type at high pressure and temperature and third type at high pressure and temperature with Kirasol-318SC as a co-solvent.

3.1 Experimental Procedure

The extraction process was carried out by using the extractor Spe-ed SFE from Applied Separations. Before beginning the experiments, all valves were closed and the reactor was heated up to desired temperature. Afterwards, the extraction vessel, which is a steel tube with wall thickness of 1 cm and volume of 100 mL, was filled with the sample LGWM 1 and closed from both sides by steel cap ends containing rubber o-rings seals in the case of overpressure. If the overpressure occurs, the rubber seals rupture and excessive gas is released from the system. Each time the reactor is depressurized, rubber o-rings are replaced, because the depressurizing process damages them. The closed extraction vessel is placed inside the reactor. Afterwards, the system is connected with the inlet and outlet CO_2 pipes and all valves are checked to ensure they are closed. On the digital control unit the oven and valve temperatures are set, the valve is set 20 °C higher than the rest of the heated system to prevent the sample precipitating inside of the tubing (Rudyk et al., 2011).
As soon the temperature reaches the desired value, the CO_2 inlet valve is opened and the gas is let from the gas tank to flow into the extraction vessel. The pressure knob is turned until the desired pressure is achieved. The maximum operating pressure is 69 MPa (Rudyk et al., 2013).
The interaction of carbon dioxide and the grease LGWM 1 occurs for 20 min under static mode. In static mode, only the inlet CO_2 valve is opened at constant temperature. Afterwards, the extraction of sample goes to dynamic mode, where the outlet valve is opened and the extract is allowed to flow into the collecting tubes. Additional gas is supplied from the gas tank and the pressure drop is automatically

regulated by the pressure knob. The test tube for collecting the extract is placed in a water bath to cool down the extract. When the extraction is done, the CO_2 inlet valve and gas tank valves are closed, the pressure knob is used to turn off the pump and the CO_2 outlet valve is opened to maximum flow. After several min, the system is depressurized, when the pressure in the reactor drops below 10 MPa the extraction vessel is dismounted from the system. During depressurization of the system some extraction is observed if the outlet valve is left open. The remains in the extraction vessel are weighed using an electronic scale. Before beginning another experiment, the extraction vessel is cleaned with hot water and 99 % Ethanol. The cap ends are cleaned and old rubber-o rings are replaced with new ones.

3.2 Numerical calculations of experimental results

The collected amount of grease W_c was calculated as a difference between weights of test tubes before and after grease collection.

The collected recovery of grease was calculated as:

$$R_l = \frac{W_c}{W_i} * 100\ \%, \tag{1}$$

where R_l is grease recovery, W_c is the weight of the collected grease, W_i is an initial grease amount of 20 g. The total recovery of the extracted grease was calculated as a difference between initial weight of grease and remaining after extraction.

The total recovery of grease was calculated as:

$$R_t = \frac{W_m}{W_i} * 100\ \%, \tag{2}$$

where R_t is the total recovery of grease, W_m is the weight of the grease extracted during experiment, W_i is an initial amount of grease equal to 20 g. Outgassing losses of grease (L) was calculated as a difference between total recovery of grease (R_t) and collected recovery(R_l):

$$L = R_t\text{-}R_l \tag{3}$$

The results of the experiment were plotted as Grease Recovery (%) versus Pressure (MPa). See Figure 2 and 3.

4. Results and Discussions

Supercritical Carbon Dioxide as a solvent is often used for various extraction purposes because it is non-toxic, non-flammable and has low environmental impact compared to other solvents in the market. To be considered in a supercritical state it should be above 31 ˚C and 7.4 MPa. The density of carbon dioxide increases as pressure rises, while the temperature has a detrimental effect on recovery. For example, according to National Institute of Standards and Technology, the density of carbon dioxide at 60 ˚C and 60 MPa is 0.967 g/cm^3. The broad SC-CO_2 application areas are explained by the fact that at supercritical conditions it acquires the liquid-like density and gas-like penetrating capability, which can have obvious advantages if it can be used for cleaning the internal complex configuration of the bearings.

The first extraction test was conducted by pure carbon dioxide. 20 g (+/- 1 g) of grease were introduced into a supercritical carbon dioxide extractor. The results of extraction are shown in Figure 2. At 50 °C and 30 MPa for 20 min of interaction, 2 % was extracted. During second trial at 60 °C and 40 MPa for 20 min, an additional 3 % of grease was extracted. The extracts became more viscous than the initial samples. The double interaction during 20 min (40 min) was made because the amount extracted had no relative value and it was required to observe if by increasing temperature and pressure more grease could be extracted. The highest total recovery of 26 % and collected of 18 % were achieved at 60 MPa. The outgassing decreased from 14 % at 30 - 40 MPa to 8 % at 60 MPa.

A second batch of experiments were carried out by carbon dioxide modified with addition of 3 mL of Kirasol-318SC to interact with the grease (~20 g) at 50 MPa and 60 MPa for 20 min each; both trials conducted at the same temperature of 80 ˚C. Plotted results can be observed in Figure 3.

At 50 MPa the total recovery was 28 % and at 60 MPa 34 %, at 50 MPa a collected recovery of 16 % and outgassing losses of 12 %, for 60 MPa 12 % and 22 % respectively. Increasing 10 MPa pressure resulted in 6 % extra total recovery, the recovery collected decreased by 4 %, the reason is that at higher pressures the resulting mixture of grease, carbon dioxide and kirasol outgassed 10 % more. The third and last trial made was at 60 MPa and 80 ˚C for 20 min, this time no co-solvent (Kirasol-318SC) was added. The objective was to observe the changes between using a co-solvent versus pure carbon dioxide at the same conditions. The experiment showed a decrease in total recovery of 8 % (26 %), an increase of 6 % (18 %) of recovery collected and the lowest outgassing of all experiments decreasing 14 % (8 %). Low outgassing could be explained by the interaction between carbon dioxide and the grease without a co-solvent at higher pressures and temperatures. At 50 MPa because of the kirasol presence, during extraction the sample look like yellow foam, while at 60 MPa with or without kirasol frozen sections were released by intervals. The resulted extractions at standard conditions have different physical characteristics with or without using a co-solvent. When using Kirasol-318SC the extraction has a semisolid and opaque appearance. On the other hand, without Kirasol-318SC the extract is less viscos, clearer and with a light brown colour similar to the original grease applied to the wind turbines.

The experiments were conducted using 20 g of grease in 100 mL extractor. It is known that the dimensions and design of the equipment can affect recovery. At the given conditions, the ratio of grease/carbon dioxide could be low causing low recovery values. The chance exists to obtain higher recovery if an extractor of smaller size is used, for example 50 mL of volume. The extraction was conducted in one run. If to apply multiple extractions, a similar or close recovery could be also expected. The total and collected recovery differed by average 14 % in both cases of pure and modified carbon dioxide.

The very high pressures needed to reach relatively high extraction recovery of 26 % by pure CO_2 and 34% by modifying with kirasol, do not make this method suitable on a practical scale. However, other observations showed that this method could be implemented for cleaning the grease from contaminants. The extracts of grease after carbon dioxide have a transparent light color containing no dust. It can imply that treating grease by SC-CO2 could be re-used.

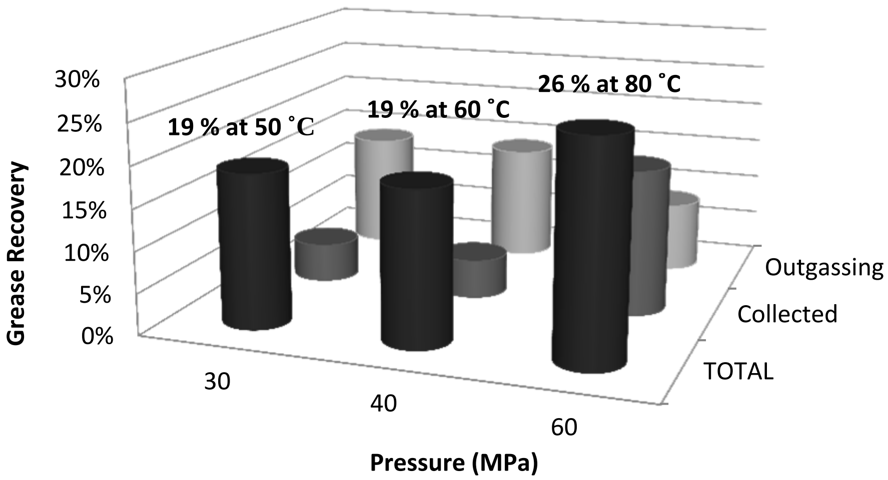

Figure 2: Results of Experiments at 50, 60, 80˚C temperature SC-CO_2

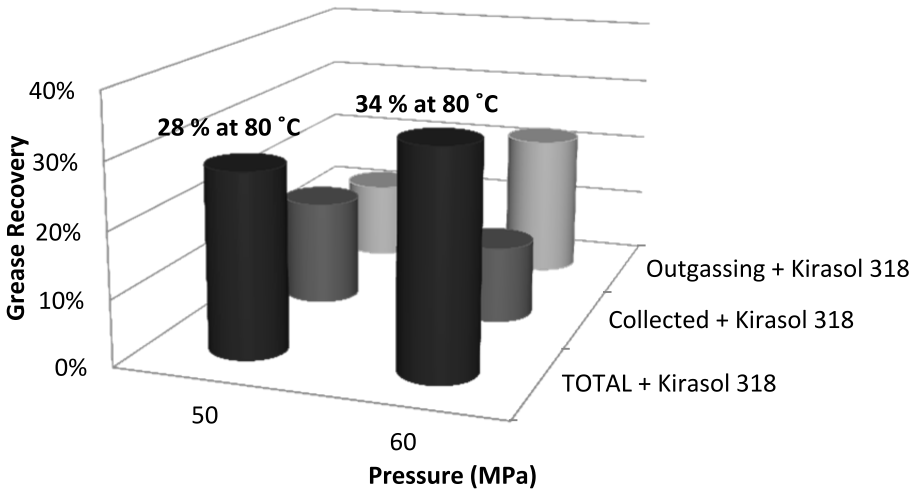

Figure 3: Results of Experiments at 80 ˚C temperature SC-CO_2 + Kirasol-318SC

5. Conclusions

The maximum recovery above 19 % was achieved by pure carbon dioxide at pressure greater than 40 MPa. The recovery by Kirasol-318SC modified carbon dioxide obtaining a recovery of 34 % at the highest pressure tested (60 MPa). The low amount of available solute and correspondingly the low ratio of grease/CO_2 probably limited the achieved recovery. Further experiments could be carried out by increasing the amount of grease to a minimum of 40 g in the 100 mL extractor vessel; or applying the same amount in the 50 mL vessel. Although the low recovery and high pressure needed for their achievement do not allow using this method for grease removal from bearings, the obtained clean grease fractions after SC-CO2 provides the method for cleaning the used grease and possibly reusing it.
Further experiments could be carried out using different co-solvents than Kirasol-318SC which has proven to increase the recovery in this paper. Co-solvents to be used in future experiments: Ethanol which has proven to remove oil based compositions in previous experiments, Kirasol-340, Power Wash M-160, RS-492 and Ocean SM 80.

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