AIR RELEASE OF USED HYDRAULIC MINERAL-BASED OILS

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The presence of air in the hydraulic system or in the hydraulic fluid itself, either in its elementary form e.g., as an air pocket or bubble, or in the form of dissolved air, causes much inconvenience. This is manifested in the form of unwanted operation of the hydraulic system, causing accelerated ageing of the fluid, especially mineral oil. Apart from knowing the measures to prevent air intrusion into the hydraulic system, it is also important to know the tendency of each type of hydraulic oil to foam and its air release property. A discussion of the air release property of mineral oil usually refers to different types of fresh hydraulic oils. How this property is reflected and changes in the case of already used and chemically degraded hydraulic oils is discussed in the present paper.

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1 Intruduction

Air in the hydraulic fluid, in its elemental form as an air pocket or air bubbles, is certainly a very undesirable, annoying and aggressive contaminant that causes a whole range of inconveniences. From a mechanical point of view, it causes increased compressibility and too elastic operation of the hydraulic system, and, from a chemical point of view, it causes faster ageing of the hydraulic oil.

In addition to the increased compressibility of the fluid and the resulting effect on the stiffness of the hydraulic components and the entire system, slower reaction times, as well as the occurrence of oscillation in the system in a mechanical sense, air causes a whole range of other inconveniences. For example, due to the incomplete filling of the pump chamber, it also affects the reduction of the actual flow of the pump and, thus, lowers volumetric efficiency, increased heating of the pump and noise, the occurrence of cavitation and the related wear of the material, a worse lubricating effect of the liquid and a reduced load capacity of the lubricating film, the diesel effect and damage to seals and smooth surfaces, etc. Apart from that, the present air also has a negative effect on accelerated oxidation (ageing), e.g., the hydraulics, causing the formation of deposits in the tank and on the components (sludge and varnishing).

Considering the whole range of negative effects, air is undesirable in the hydraulic system and is treated as a very "aggressive" contaminant and its presence in the hydraulic system is prevented and reduced. Therefore, it is necessary to remove it and ensure that it does not enter the hydraulic system in various ways.

In the literature, we can find a whole range of different tips and recommended measures to prevent air from entering the hydraulic system (aeration) or the formation of air in the system itself. The correct design of the shape and interior of the tank, care for flawless sealing of the hydraulic connections, is definitely one set of measures. The second set of measures refers to the possibilities of air extraction. In connection with this, it is certainly necessary to vent the system carefully during the first start-up of the hydraulic system, as well as measures for the effective elimination of air bubbles. Of course, if air bubbles have already appeared in the system, e.g., in the tank, we must prevent them from accessing the suction port of the pump in any way.

When we talk about air inside a hydraulic system, we must not only think of air in its elementary form, of air bubbles. We also have to think about the non-negligible proportion of chemically dissolved air in the oil, under certain conditions, can be released from the oil and appear in its elemental form, as an air bubble.

Chemically bound, dissolved air in the hydraulic fluid itself and its negative effect are mentioned much less, although we know that in mineral hydraulic oil there is from 7 % to 9 %, or even a few more percent, of dissolved air. Dissolved air cannot be seen with the naked eye, and since it is not present and visible in its elemental form as an air bubble, it does not cause the mentioned harmful effects directly in this form. Therefore, in this form, it is of secondary importance, and affects the operation of the device and the condition of the oil. The situation changes when, due to a change in pressure, the pressure in a local part of the hydraulic system falls below the value of the vapour pressure (a certain negative pressure), the dissolved air is released as an air bubble.

2 Mechanism of air bubble release

The presence of air in various forms and in fluids has long been the subject of many studies. The same applies to studies related to the knowledge of the physical background of air generation and release, as well as their influence on the operation of the hydraulic system. The findings were summarised by many other authors. ([1] to [11])

When air bubbles appear, regardless of the cause of their origin, we must remove them from the hydraulic system as quickly as possible. The efficiency of the elimination of air bubbles depends on many factors: on the shape and dimensions of the tank, on the flow conditions in the tank, on how the hydraulic fluid is returned back to the tank, on the operating conditions in the hydraulic system, e.g. the operating temperature, and also from the type of hydraulic fluid installed, most often hydraulic mineral oil.

At the same time, we must not forget the presence of other contaminants, such as water and solid contaminants, and the degree of fluid degradation, which all affect the effectiveness of the released air additionally.

2.1 Solubility of gases in oil

As mentioned, in addition to aeration, the proportion of dissolved air is important. In general, lubricating oils, including hydraulic oils, can dissolve significant amounts of gases (here, air). In addition to the type of base oil, the amount essentially depends on the pressure and the temperature. The degree of refinement of a mineral oil, the viscosity and the presence of active ingredients do not have a pronounced influence on the air solubility. The Henry-Dalton law applies to the dissolved gas volume in ml:

$$V_{Gas} = \alpha_V \frac{V_{Oil}\, p_2}{p_1} \qquad \text{[ml]} \qquad (1)$$

Table 1 gives approximate values of dissolved air in percentages, typical for different lubricating oils under normal conditions (20 °C and 1013 mbar). [6]

Table 1: Dissolved air in the lubricating oil

Fluid type	Bunsen coefficient
Mineral based oil	0.07 to 0.09
Silicone oil	0.15 to 0.25
Phosphate ester	About 0.09
Vegetable (bio) oil	About 0.09
Water	About 0.0187

The values listed in Table 1 show that the volume content of air in mineral hydraulic oils is between 7 % and 9 %. The Bunsen coefficient gives the volume ratio between the amount of gas dissolved in a fluid under normal conditions and the volume of the fluid. The dissolution of air bubbles when the pressure increases requires a certain amount of time. For mineral oils with a low viscosity (around 10 mm^2/s at 40 °C) and 20 bar, this amounts to around 20 s. An oil with a higher viscosity, 40 mm^2/s at 40 °C, requires around 60 s. [6] With increasing pressure, the solubility of air in mineral oil increases according to Henry Dalton's law.

For mineral oil products, the solubility of various gases can be calculated according to the ASTM method D 2779. It is only necessary to know the density value of the petroleum product and the type of dissolved gas.

Standard ASTM D 3827 specifies a calculation method that applies not only to mineral oil products, but also to other organic fluids (synthetic oils). The separation of air bubbles when depressurising occurs much faster than the gas absorption when the pressure increases.

The solubility of air decreases with the increasing viscosity of a base oil, i.e. with increasing average molecular weight, Table 2. [12].

Table 2: Dissolved air in the lubricating oil

Average molecular mass [g/mol]	Volume content of air [%]
670	7.83
610	7.92
570	8.43
530	8.78
400	9.03

Note: The density and molecular weight of a chemical are directly proportional to each other, and the density and volume of a chemical are inversely proportional to each other. As the molecular weight of a chemical increases then the density of the chemical increases.

2.2 Finely distributed air in the lubricating oil

In addition to dissolved air, lubricating oils can absorb additional amounts of air, distributed finely as the disperse phase during operation. This distribution of air in oil is often called aero-emulsion, air emulsion or also spherical foam. Air-in-oil dispersions are undesirable for the operation of hydraulic systems in almost all cases, since a number of (already mentioned) disadvantages arise from the presence of free air. [13], [14], [15]

Air dispersed in oil leads to an increase in viscosity, which can be estimated using the following approximation equation ([16]):

$$\eta_{Air} = \eta_{Oil} + \eta_{Oil} \cdot 0.0015 \cdot X \quad (2)$$

The equation shows that a volume content of 10 % air in the oil leads to a viscosity that is around 15 % higher.

The distribution of undissolved air in the lubricant can be reduced by the already mentioned design measures, and/or by the composition of the oil. The constructive possibilities include the following measures, some of which have already been mentioned, such as: Low oil circulation number due to large oil volume, low height of the oil tank, long distances between the oil entry point in the tank and the intake line, air release devices provided, attach the intake manifold as low as possible below the surface and avoid sharp edges of the deflections in the system.

The material factors of hydraulic oil, which play an important role in the elimination of air, are: The degree of refining of the mineral oil, the viscosity and the presence of certain active ingredients, e.g., the presence of water, oil ageing products, and also the cleanliness level of the oil.

All of these influential factors also affect the speed and efficiency of the elimination of air bubbles from the fluid.

2.3 Air release mechanism

The theoretical rise time of an air bubble in clean mineral based oil can be calculated with a good approximation using Stok's law. It is proportional to the kinematic viscosity of the fluid, and inversely proportional to the square of the bubble`s diameter. The buoyancy force of an air bubble is expressed as [11]:

$$F_{\mathrm{Buo}} = \frac{4}{3}\pi\,(\rho_{\mathrm{Fl}} - \rho_{\mathrm{Air}}) r^3 g \qquad [\mathrm{N}] \tag{3}$$

Consideration of the drag force in the motion of spherical bodies, according to Stokes, for very small Reynolds numbers:

$$F_{\mathrm{Drag}} = 6\,\pi\,\eta\,v\,r \qquad [\mathrm{N}] \tag{4}$$

leads to an expression for the rate of rise of the air bubble:

$$v = \frac{2}{9}\,(\rho_{\mathrm{Fl}} - \rho_{\mathrm{Air}})\,\frac{r^3\,g}{\eta} \qquad [\mathrm{m/s}] \tag{5}$$

Here, in equations (3), (4) and (5), *r* represents the radius of the bubble, ρ_{Fl} the density of the fluid, and ρ_{Air} the density of the air.

According to research by Hayward [16], the most commonly encountered bubble diameter is 0.25 mm to 0.5 mm. The operating viscosity for most industrial hydraulics is between 20 mm²/s and 30 mm²/s. According to this, the time it takes for a bubble to rise a metre in still oil is theoretically about 6 to 9 minutes on average. Since the viscosity of a hydraulic fluid depends very much on the temperature, the air bubbles rise faster at higher temperatures due to the lower viscosity. The actual rise time is considerably longer, depending on the type of oil, impurities/contaminants and water content, so this fact should be taken into account sufficiently when designing the oil tank.

Based on the Stokes equation, it can be seen that the rate of bubble rise decreases as the bubbles become smaller, Figure 1.

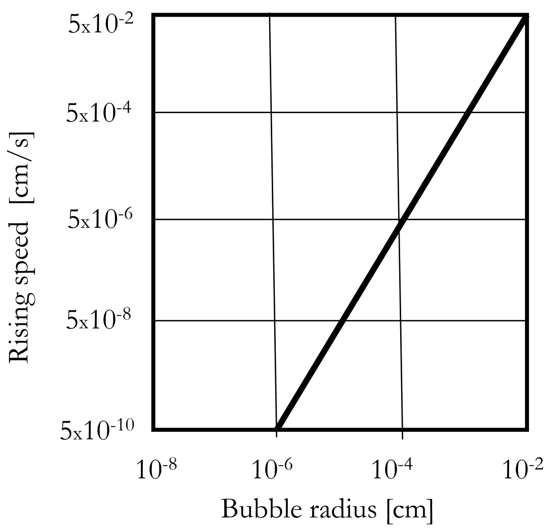

Figure 1: Rising speed of air bubbles depending on the bubble radius.
Source: own.

The ability of a fluid to remove dispersed air bubbles is called air release capacity – LAV (The commonly used abbreviation LAV for air release capacity originated from the German language: Luftabscheidevermoegen). Apart from the abbreviation LAV, the abbreviation ARV - Air release value is also often used for the same purpose.

The LAV of mineral oils is affected by viscosity, temperature and the presence of additives. Based on Stoke's law for the effect of viscosity, the higher the value of viscosity, the slower the air release. A general relationship that applies to all base oils cannot be given, because, depending on the origin and refining process, there is a different interfacial tension, and, thus, a different bubble size, Figure 2.

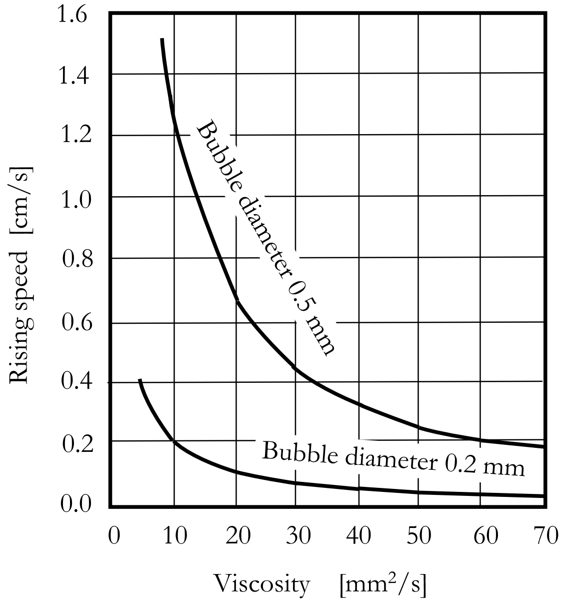

Figure 2: Theoretical rising speed of air bubbles of different diameters, depending on their viscosity.
Source: own.

The viscosity value is influenced greatly by the temperature of the oil. As the temperature increases, and, consequently, the viscosity decreases, the LAV behaviour improves.

All active ingredients that reduce the surface tension of the liquid have a negative effect on the LAV. In the case of corrosion inhibitors, detergents and oxidation inhibitors, this effect is generally neglected.

3 LAV Method of various hydraulic fluids

The standardised method for determining the LAV is the so called Impinger-method according to the DIN 51 381 Standard. For this purpose, air is blown through a capillary into the oil in an Impinger gas washing bottle at a defined temperature for seven minutes. The release of the dispersed air is monitored with a hydrostatic balance, by measuring the density until the value of the air-bubble-free sample is reached. The LAV is given in minutes for the time after which the oil still contains 0.2 % by volume of dispersed air.

There are several standard and non-standard methods for determining foaming, air content and its elimination, and they are more or less similar (see [17]). Today, the most widely used method of determining LAV is according to the ASTM D 3427-19 Standard. The test procedure is performed under a standardised set of test conditions, and hence permits the comparison of the ability of oils to separate entrained air under conditions where a separation time is available. [18]

According to the ASTM D 3427-19 Standard, the time required for the fluid to release the contained air is measured at different temperatures, at 25 °C, 50 °C and 75 °C. For the practitioner, the most interesting is certainly the performance of the test at 50 °C, which is considered as the recommended operating temperature, at which the hydraulic device also operates most of the time.

Depending on the composition of the hydraulic fluid, both in terms of base stock and the additive package it contains, the air release properties can vary substantially. Figure 3 shows a range of air release values associated with different mineral oil types. [19], [20]

	Oil	Grade	Minutes to 0.2% vol. air	
			25°C	50°C
A	Hydraulic	ISO 32	—	3
B	Turbine	ISO 32	4	2
C	Hydraulic	ISO 46	—	6
D	Turbine	ISO 46	7	3
E	Turbine	—	10	5
F	E + 1.0% oil J		10	5
G	E + 0.5% water		56	—
H	Hydraulic	ISO 100	—	13
I	Turbine	ISO 100	14	6
J	MIL-L-2104B diesel	SAE 30	77	—
K	J + 0.5% water		115	—

Figure 3: Air release properties of various oil. [19]

When it comes to air bubbles in oil, the results usually refer to fresh hydraulic oils or other types of hydraulic fluids. However, it is (almost) not stated anywhere precisely, and possibly given a limit value, how it is with the elimination of air bubbles in variously degraded used oils.

4 Air release properties of used mineral hydraulic oils

It is true that the air release of diverse types and the composition of fresh oil is undoubtedly important, but in most cases of industrial use, there is a much larger amount of used oil in hydraulic systems than fresh oil. There is also no guarantee that efficient air release of fresh oil will ensure efficient air release when the same oil will be degraded. For this reason alone, it makes sense to look for correlations between different levels of oil degradation and changes in the physical-chemical properties of the oil and the ability to eliminate air. The degree of air release could, perhaps, be one of the parameters on the basis of which we could judge the suitability of further use.

The air release capacity and the tendency to foam are influenced negatively by contaminants such as particles and water, as well as oil products, e.g., by the increase in viscosity as a result of oil oxidation and additive consumption. Also, the mixing of different types of oil has an effect on the air release capacity and the tendency to foam, e.g., by the entry of incompatible additives. Contaminants can arise from both external and internal sources. Examples of external sources can be other types of oil, other fluids, e.g., water, and dirt. The presence of water can reduce viscosity, since it becomes emulsified. Figure 3 includes some examples of the adverse effect on air release of small amounts of water.

Also, the products of the thermal degradation process or oil ageing lead to a change in viscosity and density. The same applies to acidic oxidation products, which, in turn, lead to changes in LAV. [19]

4.1 LAV of accelerated aged oils

In order to determine changes in the physical and chemical properties of variously degraded mineral hydraulic oils, we used our own developed procedure for accelerated thermal ageing of the oil, the so-called dry thermal test. The test is similar to the TOST test, where, at an elevated temperature (150 °C), the presence of copper and oxygen in the air in the role of catalysts or accelerators of thermal oil degradation led to faster oil degradation. More details on the procedure and test execution can be found in [21]. The thermal loading of the sample lasted for a certain number of hours, after which all those physical-chemical properties were measured, which are usually changed due to degradation and could also affect the LAV. The results are summarised in Table 3. Hydraulic mineral oil of the HL type and viscosity class ISO VG 46 was used for the test.

Table 3: Results of the analysis of samples after hours of accelerated ageing

Hydraulic oil HL ISO VG 46	HL 0	HL 40	HL 60	HL 110
Testing time [h]	0	40	60	110
Colour [-]	2.0	6.0	> 8.0	> 8.0
Density @ 20 °C [kg/m³]	876	876	877	879
Viscosity @ 40 °C [mm²/s]	46.45	48.35	49.30	62.18
Viscosity @ 100 °C [mm²/s]	6.91	7.06	7.18	8.08
Neutralisation No. [mg KOH/g]	0.54	0.65	0.72	1.9
FT-IR Oxidation [-]	0.31	0.43	0.64	2.30
LAV @ 50 °C [min]	**5.7**	**6.1**	**5.8**	**6.1**
Foaming - Sequence I [ml/ml]	**0/0**	**20/0**	**0/0**	**610/0**
Foaming - Sequence II [ml/ml]	**30/0**	**20/0**	**10/0**	**30/0**
Foaming - Sequence III [ml/ml]	**0/0**	**0/10**	**0/0**	**570/50**
Electrical conductivity [pS/m]	607	853	1121	9219

Table 3 shows clearly those physical-chemical parameters and their values that are at the forefront of consideration - LAV and foaming. Increasing values for viscosity, neutralisation number, FT-IR oxidation and also values for colour and electrical conductivity, show clearly the degree of oil degradation as a result of thermal stress under the influence of the ageing process accelerators.

It is evident and interesting from the results that, after the accelerated thermal ageing of the oil, the value of the LAV had hardly changed (small fluctuations in the value are a possible result of the precise assessment of the determination of the end of the test - the difference in times amounts to 6%). In principle, changes in LAV coincide with changes in density, which changed minimally. However, the viscosity of the aged oil changed significantly, and the foaming of the oil worsened a lot.

Since accelerated thermal ageing of the oil was used in this case, in which no noteworthy changes in LAV were detected, it is certainly reasonable to check whether a similar pattern of changes also occurs in "naturally" aged oils - after a certain period of operation. It should be noted that the hours of the accelerated thermal degradation process are equivalent to several months, or even years, of naturally degraded oil.

4.2 LAV of naturally aged oils

Similar changes in the quantities mentioned in the previous chapter can also be expected in the case of naturally aged oil, on a real hydraulic device, except that the time of appearance of the change is significantly longer (several tens of days, or even months).

Monitoring of the state of the physical-chemical parameters of hydraulic oils in industrial use is usually carried out at certain time intervals, usually every two months. In this case, the test operator usually does not know the actual number of operating hours during this period, so there may be deviations or less credible results. Also, other operating parameters, such as, e.g. ambient temperature, ambient humidity, or something else.

Table 4 shows only some of the parameters of an otherwise wide range of comprehensive analysis for the case of naturally degraded oil and a two-month sampling interval for a period of eight months. The values for LAV and foaming are in the foreground. ISO VG 46 hydraulic mineral oil was used as the oil.

Table 4: Comparison of viscosity, foaming, and air release properties of naturally degraded hydraulic oils

Sample	Hydraulic oil ISO VG 46					
Date	9.2022	11.2022	1.2023	3.2023	2.2023	7.2023
Density @ 20 °C [kg/m³]	871	871	871	871	871	871
Viscosity @ 40 °C [mm²/s]	45.76	46.43	46.48	46.60	46.31	46.59
Viscosity @ 100 °C [mm²/s]	7.199	6.859	6.886	6.963	6.939	6.976
LAV @ 50 °C [min]	**6.3**	**4.8**	**4.7**	**5.4**	**4.4**	**4.4**
Sequence I [ml/ml]	**0/0**	**0/0**	**0/0**	**0/0**	**190/0**	**430/0**
Sequence II [ml/ml]	**70/0**	**20/0**	**40/0**	**50/0**	**30/0**	**30/0**
Sequence III [ml/ml]	**20/0**	**20/0**	**0/0**	**270/0**	**30/0**	**480/0**

Even in the case of naturally aged oil, it turned out that the LAV value changes very little, but the foaming much more. The release of air depends much more on the type of fluid, basic physical-chemical values such as density and viscosity, and also on the type of additives present.

6 Conclusion

The operation of the hydraulic system is certainly influenced by the type of built-in fluid and its basic material properties, such as density and viscosity, temperature behaviour, type of additives and base fluid, and more, as well as the presence of air and its ability to be released. As is known, the air present in the hydraulic fluid causes a whole range of negative effects, from a direct effect on the dynamic behaviour of the system, to an indirect effect on the faster ageing of the fluid, for example hydraulic mineral based oil. For this reason, the fluid's ability to eliminate air from the system as quickly as possible is one of the important properties that may not be given enough detail. The latter property is determined by a standard test to determine the air release.

The paper presents the mechanisms that affect air release, and summarises some findings from some previous studies. Typically, these findings apply to unused, fresh hydraulic oils. In the continuation of the paper, the focus of discussion is on the ability to release the air of used, already degraded hydraulic oils. The results related to the efficiency of air release and the occurrence of foaming are shown for two cases: for the case of accelerated thermally degraded oil, and for the case of naturally degraded oil under real industrial operating conditions.

Both in the case of oil with accelerated ageing and naturally aged oil of the same type, it was found that the LAV value changes very little, but it foams much more. Based on this, we can conclude that the type of liquid, especially its density and viscosity, as well as the type of base oil, have a much greater impact on LAV.

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