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# Bubble Evolution in Bushings

## ABSTRACT

When the temperature of an oil-impregnated bushing is increased, nitrogen from the expansion space is dissolved into the oil. If rapid cooling takes place, the oil becomes oversaturated and bubbles may appear. Such bubbles have caused partial discharges and dielectric failures during transformer factory tests where a heat run was followed by fast cooling and dielectric testing.

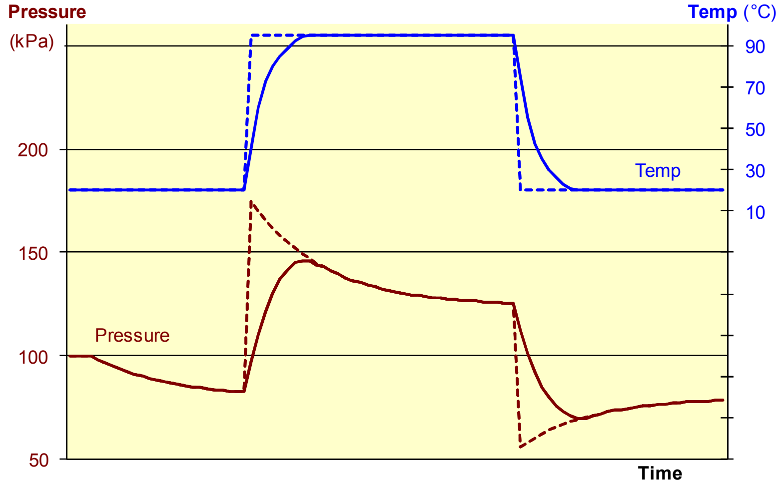
This paper will describe the method to calculate the oversaturation and factors influencing it such as duration of heat run (time constant), internal pressure level in bushing, size of expansion space, temperature during heat run and the effects of ventilating the bushing are also described.

Oversaturation with bubble formation is primarily a problem during factory transformer testing. In service, the temperature reductions are slower and the voltage stress is lower.

Finally a strategy to manage the risk of bubbles is presented.

## INTRODUCTION

Oil impregnated condenser bushings normally have a gas space located at the top of the bushing. The function of this gas space is to accommodate the expansion and contraction of the oil volume due to temperature changes. When the temperature within the bushing increases due to load, the nitrogen in the gas space dissolves into the oil. If the load is removed and the bushing is rapidly cooled, the oil becomes oversaturated with nitrogen and gas bubbles may evolve in the oil. The presence of these bubbles in the oil can have the effect of reducing the dielectric strength of the oil and partial discharge activity can commence within the bushing. Partial discharge can lead to dielectric failure of the bushing. This paper includes a discussion of the general physics of this phenomenon. It also includes how various parameters affect the severity of gas bubble evolution and suggests actions which will mitigate the problem during factory transformer testing.



100 kPa = $10^5$ N/$m^2$ = 1 bar ≈ 1 atm ≈ 14,5 psi

All pressures are expressed in absolute values.

Bushing temperature and pressure vs. time
Figure 1

## Gas Bubble Evolution

The bushing gas space is designed so that it will permit the oil volume to expand within the required temperature range without exceeding design limits for bushing internal pressure. The ratio between oil and gas volumes is typically in the range from 4:1 to 7:1. In the ideal example shown in Figure 1, a new bushing is impregnated and filled with de-gassed oil and the expansion space is flushed with air or nitrogen, but not pressurized, before the bushing is sealed. During transport and storage, nitrogen molecules dissipate into the oil and the pressure decreases slightly. At service load, the thermal expansion of the oil and gas increases the pressure. In Figure 1, we show the effects of temperature and time on the internal bushing pressure. The dotted lines indicate a theoretical case where the immediate pressure rise is separated from the following additional dissipation of gas into the oil. The solid lines represent the realistic case where the temperature rise takes some time and the dissipation limits the thermal pressure rise.

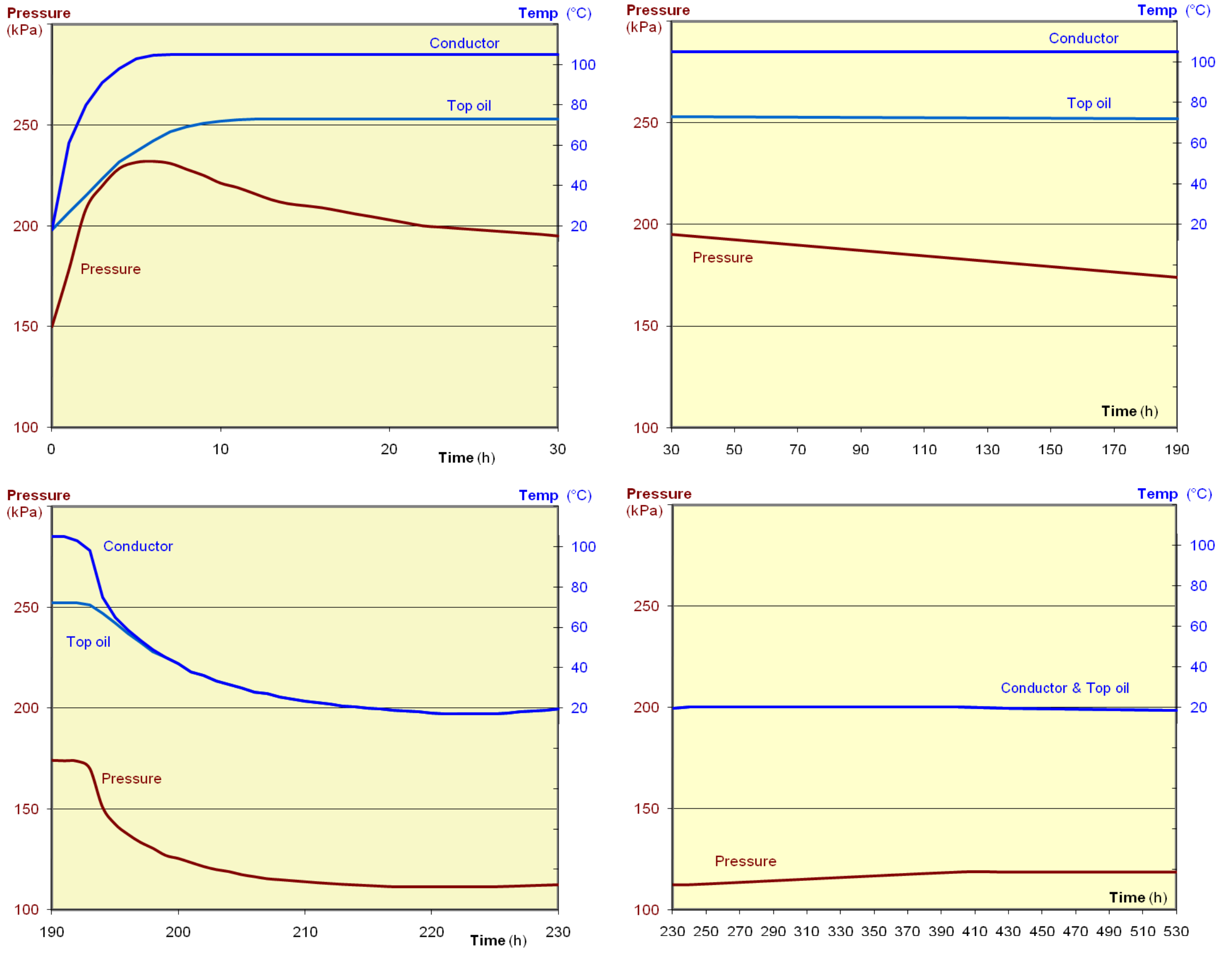
When the bushing cools down, the oil can hold less gas and gas molecules leave the oil and go back into the gas space. The lower gas pressure due to shrinking oil is also a driving force for this gas transport. If the cooling and pressure drop are rapid, the gas cannot leave the oil fast enough, the oil becomes oversaturated and small bubbles may appear in the oil volume. If the previous state with high temperature and high pressure continued for a long period, the oil is more saturated when the cooling begins, increasing the probability of bubble formation.

## TIME CONSTANT

The time needed to saturate the oil with gas is highly dependent on the bushing size and the service conditions. Factors causing a fast dissipation are:

1. Bushing for lower voltages (BIL 170 kV – 750 kV) with short distance for gas molecules to reach all oil spaces.
2. Internal thermal gradients generating internal oil circulation.
3. Small condenser core.
4. Transportation in horizontal position with a large oil surface area exposed to gas.

ABB tested a generator step up transformer bushing for three weeks. The bushing (Type GOH) was rated 25 kA and 170 kV BIL. This is a relatively small bushing; the height of the oil and gas space is about 0,5 m (20 inches). The test started and ended at an ambient temperature of 20 °C. The bushing was mounted in a test tank with oil (representing transformer top oil) heated to 70 °C and the central bushing conductor was heated to 105 °C (representing rated load) thus generating internal oil circulation. The bushing was initially filled with degassed oil at room temperature and then the gas space was pressurized to 150 kPa and sealed.



**Pressure variation caused by gas dissipation in GOH bushing**
**Figure 2**

The set of four plots in Figure 2 show the relationship between bushing pressure, top oil temperature and conductor temperature over a 530-hour temperature cycle where the bushing returns to ambient temperature. Even though the plots represent a more complex heating and cooling pattern than the initial ideal case, we can estimate the time constant to be at least 25 hours at the start and the early part of the heating period. This means that 63% of the gas molecules needed to saturate the oil have found their way into the oil after 25 hours, but there is still space for 37%. After another 25 hours, another 23 percentage units have entered the oil and there is still space for 14%. The closer the oil is to being saturated at the high temperature, the higher the risk of oversaturation and bubble evolution during cooling. The tested bushing, because of its geometry, is of a “fast time constant” type, most other bushings have longer time constants and obviously, the duration of the high temperature period is of importance.

## INSULATION STRENGTH AT LOW INTERNAL PRESSURE

Concerns have been raised that a low internal pressure in the bushing may reduce the dielectric withstand strength of the oil-paper insulation. A simulated laboratory test with rapid pressure changes may generate bubbles in a way that is not representative for normal service. In a test with a sequence not generating bubbles, a new GOB 250 kV BIL bushing was successfully routine tested up to its designed power frequency withstand level of 120 kV plus an additional withstand test at 140 kV. The tests were

performed at 40 kPa, 100 kPa, and 150 kPa absolute pressures. At the highest voltage, small partial discharges (3-8 pC) with the higher value at the lowest pressure were recorded. When the pressure was increased, the partial discharge was reduced to 3-4 pC, probably because a not yet fully impregnated minor void was compressed by the higher pressure. When the voltage was reduced to 115 kV the partial discharge extinguished and came back to the background level of 2-3 pC at all pressures.
In reference 1, the author measured the influence of pressure on the breakdown voltage of insulating oil. The influence was small, i.e. the breakdown voltage was reduced by 5% when the pressure was reduced from 100 kPa to 50 kPa.

As long as bubbles are not created, the bushing can withstand high electrical stress at low internal pressure. The dielectric withstand is practically the same if the bushing operates in the pressure range 50-150 kPa or 80-180 kPa. The slight differences mentioned above are well within the natural variations covered by the safety margins in the test levels.

## SERVICE CONDITIONS

The bubbles in oil phenomenon primarily occurs during routine transformer testing when a heat run is followed by rapid cooling. When the load is switched off, the cooling fans may continue to run until the transformer is cooled down to room temperature. Then the dielectric tests are performed. This temperature reduction is normally greater and faster than in service, where fans are switched off at around 50 °C. Thus the risk of bubbles is less in service than it is during factory transformer tests.

Even though bubbles are less likely to occur in service, it is interesting to know if they can cause partial discharges at service voltages. A few partial discharge inception voltages have been recorded at transformer tests indicating that even with bubbles, the partial discharge ignition voltage is above the service voltage.

**Table 1**
**Partial discharge inception voltage**

| | | kV | kV | kV |
|---|---|---|---|---|
| Service voltage | phase-phase | 230 | 24 | 52 |
| | phase-earth | 133 | 14 | 52 |
| pd ignition | phase-earth | 443 | 35 | 120 |
| pd extinction | phase-earth | 246 | | |
| Transformer test voltage | phase-earth | 475 | 50 | 95 |

## CALCULATIONS

There have been several published papers, which discussed oversaturation and gas evolution in transformer oil. This phenomenon was described as early as 1958 (reference 2) where Degnam et al presented a comprehensive explanation of gas bubbles in sealed transformer tanks. The detailed calculation sequences are not repeated here, but the basic relations are given in the Appendix. The oversaturation factor is used here as a measure of the risk of bubbles. The oversaturation factor is defined as the instantaneous concentration of gas in oil divided by the theoretical equilibrium concentration at the instantaneous temperature and pressure.

## Oversaturation at Different Pressures

Can the risk of bubbles be reduced with a higher or lower pressure in the bushing or by saturating the oil with gas before the bushing is sealed at the bushing factory?

Unfortunately, no; the oversaturation, and thus the risk of bubbles, remains the same as shown by the examples in Table 2. In Case 1, a typical bushing is filled with degassed oil (the gas concentration is 0 ppm) and sealed by the bushing manufacturer with the gas space at atmospheric pressure (100 kPa). After some time, 40 ppm of gas has dissolved into the oil and the gas pressure is reduced to 80 kPa. When the bushing temperature is increased, e.g. during a heat run, to 80 °C the oil expands and the gas is compressed to 146 kPa pressure. In this example the temperature rise is instantaneous, there is not time for any gas molecules to enter the oil, and the concentration remains at 40 ppm. The high pressure forces more gas molecules into the oil until equilibrium at 74 ppm and 114 kPa is reached at 80 °C by the end of the heat run. Then the temperature is (instantaneously) lowered to 20 °C again and the oil contraction and reduced gas temperature give a temporary gas pressure of 62 kPa whilst the concentration remains at 74 ppm. At 20 °C and 62 kPa, the equilibrium concentration would be 31 ppm and the oil is oversaturated with gas. This is the critical moment during the temperature cycle and the oversaturation factor 74/31 = 2,4 is used as a measure of the risk of bubbles. After some time at 20 °C, the bushing will return to the equilibrium state of 80 kPa gas pressure and 40 ppm gas concentration in the oil.

As a comparison, we present two other Cases in Table 2. In Case 2, the bushing manufacturer pressurizes the bushing at 150 kPa before sealing. In Case 3, the oil is gas saturated at atmospheric pressure and then the gas space is pressurized to 150 kPa before the bushing is sealed.

In all three cases, the oil becomes oversaturated to the same ratio, 2,4, independently of the absolute pressure level of the bushing.

**Table 2**
**Oversaturation as a function of initial pressure**

| | Case 1 | | | Case 2 | | | Case 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| Oil to gas volume ratio | 7:1 | | | 7:1 | | | 7:1 | | |
| | Temp | Pressure | Concentration | Temp | Pressure | Concentration | Temp | Pressure | Concentration |
| | °C | kPa | ppm | °C | kPa | ppm | °C | kPa | ppm |
| Initial condition | 20 | **100** | **0** | 20 | **150** | **0** | 20 | **150** | **50** |
| At equilibrium | | 80 | 40 | | 119 | 60 | | 138 | 69 |
| After instant heating | 80 | 146 | 40 | 80 | 219 | 60 | 80 | 253 | 69 |
| At equilibrium | | 114 | 74 | | 171 | 111 | | 191 | 124 |
| After instant cooling | 20 | 62 | 74 | 20 | 93 | 111 | 20 | 104 | 124 |
| Concentration of saturated oil of this temp and pressure | | | 31 | | | 47 | | | 52 |
| Oversaturation factor | | | 2,4 | | | 2,4 | | | 2,4 |

## Effect of Expansion Volume

The typical bushing with a 7:1 ratio between oil volume and gas volume is repeated in Table 3. In this case we study the effect of a larger or smaller expansion volume in Case 4 and in Case 5. Even if the expansion volume is more than doubled to the ratio 3:1 (Case 4), this temperature cycle creates considerable oversaturation. Experience has also shown that GOH bushings with a volume ratio around 3:1 can produce bubbles when subjected to rapid cooling after a heat run. On the other hand, a reduced expansion volume (Case 5) does increase the oversaturation so the size of the expansion volume cannot be neglected even though the bubble phenomenon cannot be avoided by an increased gas space alone.

### Table 3
### Oversaturation as a function of expansion volume

| | Case 4 | | | Case 1 | | | Case 5 | | |
|---|---|---|---|---|---|---|---|---|---|
| Oil to gas volume ratio | **3:1** | | | **7:1** | | | **12:1** | | |
| | Temp | Pressure | Concentration | Temp | Pressure | Concentration | Temp | Pressure | Concentration |
| | °C | kPa | ppm | °C | kPa | ppm | °C | kPa | ppm |
| Initial condition | 20 | 100 | 0 | 20 | 100 | 0 | 20 | 100 | 0 |
| At equilibrium | | 90 | 45 | | 80 | 40 | | 70 | 35 |
| After instant heating | 80 | 127 | 45 | 80 | 146 | 40 | 80 | 203 | 35 |
| At equilibrium | | 118 | 76 | | 114 | 74 | | 109 | 71 |
| After instant cooling | 20 | 83 | 76 | 20 | 62 | 74 | 20 | 38 | 71 |
| Concentration of saturated oil of this temp and pressure | | | 42 | | | 31 | | | 19 |
| Oversaturation factor | | | 1,8 | | | 2,4 | | | 3,8 |

## Effect of Temperature

In Table 4, we repeat the typical bushing (Case 1) and investigate the effect of heating to other temperatures. The oversaturation factor increases progressively with the temperature. For this reason, it is not recommended to subject the bushing to transformer processes such as drying at temperatures well above normal service levels. If the transformer heat run includes an initial overload to reduce the time to reach steady state, the effect on the bushing temperature should also be considered.

Bushings for the transformer low voltage side are often loaded close to their current rating whereas dielectric requirements are dimensioning the high voltage side bushings and thus the lower voltage bushings often reach a higher temperature during the heat run. This is in line with the tendency that bubbles primarily occur in bushings up to BIL 825 kV.

### Table 4
### Oversaturation as a function of temperature

| | Case 6 | | | Case 1 | | | Case 7 | | |
|---|---|---|---|---|---|---|---|---|---|
| Oil to gas volume ratio | 7:1 | | | 7:1 | | | 7:1 | | |
| | Temp | Pressure | Concentration | Temp | Pressure | Concentration | Temp | Pressure | Concentration |
| | °C | kPa | ppm | °C | kPa | ppm | °C | kPa | ppm |
| Initial condition | 20 | 100 | 0 | 20 | 100 | 0 | 20 | 100 | 0 |
| At equilibrium | | 80 | 40 | | 80 | 40 | | 80 | 40 |
| After instant heating | **50** | 106 | 40 | 80 | 146 | 40 | **110** | 214 | 40 |
| At equilibrium | | 96 | 55 | | 114 | 74 | | 134 | 98 |
| After instant cooling | 20 | 72 | 55 | 20 | 62 | 74 | 20 | 50 | 98 |
| Concentration of saturated oil of this temp and pressure | | | 36 | | | 31 | | | 25 |
| Oversaturation factor | | | 1,5 | | | 2,4 | | | 3,9 |

## Ventilated Bushing

If the bushing from reference Case 1 is opened after cooling, the pressure increases from 62 to 100 kPa and the oversaturation is reduced from factor 2,4 to 1,5; see Table 5.

### Table 5
### Oversaturation as a function of ventilation after heat run

| Oil to gas volume ratio | (7:1) Opened after heat run | | |
|---|---|---|---|
| | Temp | Pressure | Concen-tration |
| | °C | kPa | ppm |
| Initial condition | 20 | 100 | 0 |
| At equilibrium | | 80 | 40 |
| After instant heating | 80 | 146 | 40 |
| At equilibrium | | 114 | 74 |
| After instant cooling | 20 | 62 | 74 |
| With plug open | | 100 | 74 |
| Concentration of saturated oil of this temp and pressure | | | 50 |
| Oversaturation factor | | | 1,5 |

The high gas concentration at elevated temperature is a result of both the high temperature with increased gas solubility and the higher pressure. If the bushing can breathe during the temperature cycle, the oversaturation is reduced to factor 1,3 as shown in Table 6.

### Table 6
### Oversaturation as a function of ventilation during heat run

| Oil to gas volume ratio | (7:1) Opened during heat run | | |
|---|---|---|---|
| | Temp | Pressure | Concen-tration |
| | °C | kPa | ppm |
| Initial condition | 20 | 100 | 0 |
| At equilibrium | | 80 | 40 |
| After instant heating | 80 | 100 | 40 |
| At equilibrium | | 100 | 65 |
| After instant cooling | 20 | 100 | 65 |
| Concentration of saturated oil of this temp and pressure | | | 50 |
| Oversaturation factor | | | 1,3 |

## Moisture Ingress

When the top plug of the bushing is open during the heat run, part of the gas cushion is pressed out during the heating period and when the bushing cools down, ambient workshop air is sucked into the bushing. Can the moisture in this air be harmful? The following example shows that this is not the case and that the influence on the bushing power factor is negligible.

Example: High current bushing GOH 170 kV BIL and 25 kA.

Nominal expansion (gas) volume = 2,5 x $10^{-3}$ $m^3$.

Water content in air at 30 °C and 95% relative humidity = 29 x $10^{-3}$ $kg/m^3$.

If all dry gas is forced out of the expansion volume during the heat run and replaced by humid workshop air, 72 x $10^{-6}$ kg of water is enclosed in the expansion volume when the bushing is sealed.

Weight of the paper = 4 kg.

All water in the expansion volume is assumed to pass through the oil and spread evenly within the paper. Then the water content in the paper increases by 0,0018 percentage units.

The water content in a new bushing is typically in the order of 0,250%.

Then the ventilation during the heat run increases the water content to 0,252%.

The power factor of a new bushing is typically in the order of 0,4%.

There is no clear relation between the water content and the power factor, but the power factor is approximately linearly proportional to the water content and 1% extra water will increase the power factor with 0,2 percentage units. Thus the ventilation during heat run will increase the power factor marginally from 0,400% to not more than 0,401%. This bushing style has a relatively large ratio between gas volume and weight of paper. Other bushing styles are even less sensitive to a short period of ventilation.

It is important that the bushing is sealed after the testing, continuous breathing in service certainly destroys the bushing!

## RECOMMENDATIONS

In cases where experience shows that a certain bushing style in combination with a test sequence has generated bubbles, it is recommended to manage the situation by ventilating the bushing during the heat run and during the following dielectric tests. It is not necessary to pressurize the bushing during the dielectric tests. It is further recommended that any bushing subjected to over 3000 A during a specific heat run should be considered a candidate for ventilation.

In cases where extraordinarily long or severe overloads occur special consideration should be given to this issue.

If the heat run was performed with the bushing sealed and unexpected bubbles and partial discharges appear at dielectric tests, the bushing can be opened at this stage. If the bushing manufacturer has filled the bushing with degassed oil and sealed it at atmospheric pressure, this operation will increase the pressure in the bushing to atmospheric and thus instantly diminish the oversaturation.

ABB bushings type GOH, Type T and O Plus C$^{TM}$ are filled with degassed oil and sealed at atmospheric pressure. The detailed methods to ventilate the bushings are given in respective product literature.

## CONCLUSIONS

When a sealed oil impregnated bushing operates at high temperature, nitrogen gas from the expansion volume is dissolved into the oil. After rapid cooling, the oil becomes oversaturated with nitrogen and bubbles can occur.

- The degree of saturation is time dependent with a typical time constant in the order of 25 hours.
- A bigger gas space reduces the risk of bubbles, but the phenomenon may occur even if the bushing gas space is relatively large.
- If a bushing is heated to a higher temperature, the risk of bubbles increases progressively with the temperature.
- The risk of oversaturation is independent of the absolute pressure level in the bushing.
- Oversaturation with bubble formation is primarily a problem at transformer testing. In service the temperature reductions are slower and the voltage stress is lower.

The vast majority of bushing styles and transformer test sequences do not generate bubbles. However, experience has shown that some combinations are at risk and in those cases it is recommended to manage the situation by ventilating the bushing during the heat run and dielectric tests.

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## REVISIONS

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## APPENDIX
## Equilibrium Pressure and Concentration

In a rigid enclosure filled with gas and oil, the pressure and the concentration of gas in oil depend on the temperature. The initial conditions are given by the following parameters.

| | |
|---|---|
| $V_{oilinit}$ | Volume of oil at initial temperature, m³ |
| $V_{gasinit}$ | Volume of gas at initial temperature, m³ |
| $T_{Cinit}$ | Initial temperature, °C |
| $p_{init}$ | Initial pressure, Pa |
| $c_{init}$ | Initial concentration of gas in oil, kg/kg |

The density of the gas needs to be specified. For nitrogen, the ideal gas law gives

$$\rho_{gas} = \frac{p}{R_{N_2} T_K} \tag{1}$$

The gas constant is $R_{N2} = R_G/M_{N2} = 8314/28 = 29{,}7$ J/kgK and the temperature $T_K$ should be given in K, i.e. $T_K = T_C + 273$.

The density of oil needs to be specified. For NYTRO 10X, the following relation can be used.

$$\rho_{oil} = 884{,}3 \times \left(1 - 8{,}15 \times 10^{-4} \times T_C\right) \tag{2}$$

The total mass of oil in the enclosure is

$$m_{oil} = V_{oilinit} \times \rho_{oil}\left(T_{Cinit}\right) \tag{3}$$

This mass is constant since the enclosure is tight. The volume of the oil is depending on the temperature, and therefore the volume available for gas as well as the pressure due to compression of the gas depends on the temperature. Assuming that the volume of oil is a function of temperature but not of pressure, we get

$$V_{oil}\left(T_C\right) = \frac{m_{oil}}{\rho_{oil}\left(T_C\right)} \tag{4}$$

The volume of gas is the part of the total enclosure volume that is not occupied by the oil.

$$V_{gas}\left(T_C\right) = V_{oilinit} + V_{gasinit} - V_{oil}\left(T_C\right) \tag{5}$$

The density of the gas in the gas volume at temperature $T_C$ is

$$\rho_{gas}\left(T_K, p\right) = \frac{m_{gas} - c\left(T_C, p\right) \times m_{oil}}{V_{gas}\left(T_C\right)} \tag{6}$$

The total mass of gas, which must be constant, is

$$m_{gas} = V_{gas}(T_C) \times \rho_{gas}(T_K, p) + c(T_C, p) \times m_{oil} \tag{7}$$

After long time at stable conditions, equilibrium distribution of gas between the gas volume and gas dissolved in oil will be attained. The equilibrium concentration can be approximated by the following formula.

$$c_{eq}(T_C, p) = \{c_{ref} \times [1 + \gamma \times (T_C - T_{ref})]\} \times \frac{p}{p_{ref}} \tag{8}$$

For nitrogen in transformer oil, we can assume $c_{ref} = 5 \times 10^{-5} = 50$ ppm and $\gamma = 0{,}005\ K^{-1}$, for $T_{ref} = 20$ °C and $p_{ref} = 10^5$ Pa = 1 bar. (The parameter $\gamma$ has different values depending of type of gas and type of liquid. There are many combinations of gas and liquid that have negative $\gamma$.)

Using the equations above, it is possible to derive an expression for the equilibrium concentration as function of initial conditions and temperature. After some algebra, we get

$$c_{eq}(T_C) = \frac{A(T_C) \times m_{gas}}{(m_{gas} - c_{init} \times m_{oil}) + A(T_C) \times m_{oil}} \tag{9}$$

where

$$A(T_C) = \{c_{ref} \times [1 + \gamma \times (T_C - T_{ref})]\} \times \frac{p_{init}}{p_{ref}} \times \frac{V_{gasinit}}{[V_{gasinit} - (V_{oil}(T_C) - V_{oilinit})]} \times \frac{T_K}{T_{Kinit}} \tag{10}$$

The pressure is obtained from combination of Eq. (9) and Eq. (8).

$$p = \frac{c_{eq}(T_C) \times p_{ref}}{c_{ref} \times [1 + \gamma \times (T_C - T_{ref})]} \tag{11}$$