



flucon Report.

Optical analysis of dispersed gas in oil

as produced by Flucon Oil Aeration Machine (FOAM)

Part 1: Bubble sizes at atmospheric pressure

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1 Introduction

Fluid aeration, or oil aeration specifically, is a common phenomenon to appear in lubricated machinery and hydraulic components. Through different causes like variation of pressure and temperature or hydraulic deficiencies, e.g. suction-sided leakage, air gets undissolved or entrained in a fluid-carrying system. As the compressible part of the two-phase mixture with a comparatively low density, the gas phase is volatile and takes forms that are highly dependent on the pressure.

In general gas-in-fluid dispersions can be differentiated by their bubble diameters:

| Bubble diameter | Stability of two-phase-mixture* | Rising speed of bubbles* | Dispersion type |
|-----------------------|---------------------------------|--------------------------|---|
| $10^{-9} - 10^{-6}$ m | high | low | microdispersion (gas lyosole) |
| $10^{-6} - 10^{-3}$ m | medium | medium | bubbly dispersion (aeroemulsion) |
| $> 10^{-3}$ m | low | high | Coarse dispersion, large bubbles or air pockets |

Fig.1: classification of dispersions

(*not applicable for surface foam)

Since most gas dispersions and especially motor- and hydraulic-oil-based dispersions are volatile mixtures that degas when they stagnate under atmospheric pressure and gravitational acceleration, it's common that all three types of bubbles coexist in dispersions.

Degassing is increased with increasing bubble diameters, while the rising speed of gas bubbles depends on both bubble diameter ($2 r_B$) and viscosity η of the surrounding fluid phase. It can be calculated as follows [STOKES]:

$$v_B = \frac{2 r_B^2 g (\rho_F - \rho_B)}{9 \eta}$$

with g = acceleration of gravity [$\frac{m}{s^2}$],
 ρ_F = fluid density [$\frac{kg}{m^3}$],
 ρ_B = gas density [$\frac{kg}{m^3}$].

In addition, as shown in fig. 2, the rising speed of a bubble is increased overproportionally by increasing bubble diameter, due to the overproportionally increasing volume of the low-density gas phase.

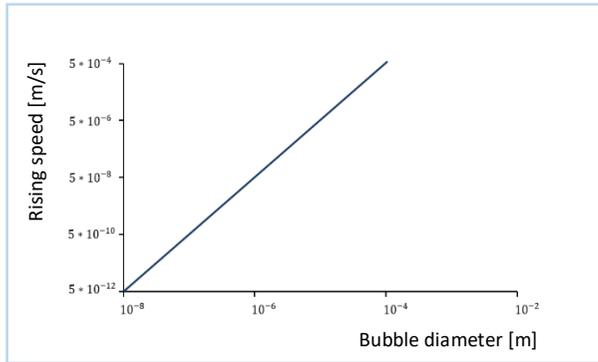


Fig.2: rising speed over bubble diameter [exemplaric viscosity $\eta = const.$]

2 Test Setup

A Flucon Oil Aeration Machine FOAM XL-x is used to aerate 30 Liters of automatic transmission fluid inside a test reservoir. The tank is equipped with a 2 kW screw-in heater in order to bring the oil to different test temperatures. In addition the cooler of the FOAM compensates for the heat generated as byproduct of the aeration process so that temperatures can be kept constant.

Aeration is performed by connecting the FOAM to the reservoir through two braided hoses with 25 mm of diameter. The aeration monitoring is carried out with the CG sensor of the FOAM. This sensor is connected to a secondary pump which runs the aerated oil from the reservoir to the sensor through 9,5 mm hoses. The sensor has a nominal width of 3/8".

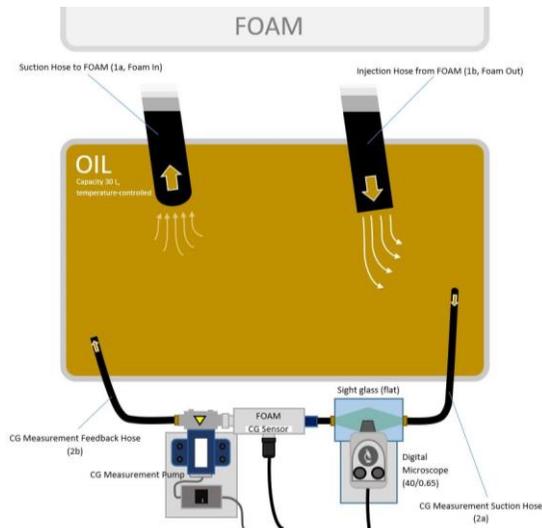


Fig.3: Scheme of flucon setup with FOAM, test reservoir, CG sensor, sight glass and microscope

In front of the sensor a flat sight glass was installed. It consists of three heat-proof glass layers with a rhombic cut-out in the middle layer for the oil to flow through and a scale on the bottom of the top glass. The glass thickness was kept as low as 3 mm in order to force the oil to flow in a quasi-2D level and minimize the magnifying effect of the top layer. The flowing oil can now be observed through a transmitted-light microscope with a digital ocular.

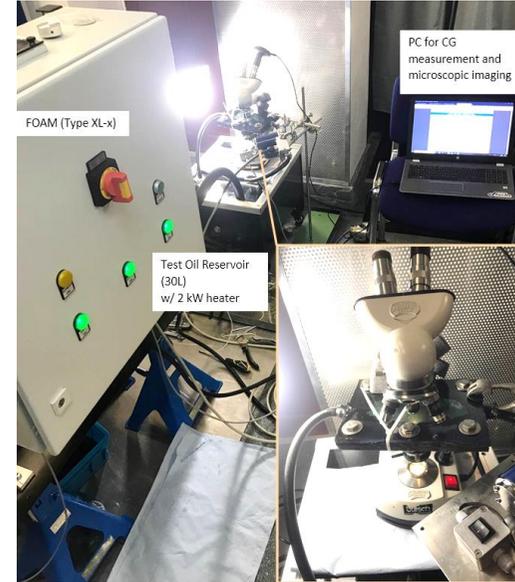


Fig.4: photo of test rig, microscope with sight glass

Furthermore the flow rate was set to approx. 1 l/min to keep negative pressures on the suction side at a minimum. This allows measurement and observation of the gas phase close to atmospheric pressure, thus without influence on the compressibility/bubble volume and solubility/bubble number. Following flucon standards this also brings comparability independently from the flow conditions.

The oil-air mixture produced in the FOAM was released to the open test tank, which allows the dispersion to expand after compression of the aeration process. Therefore the bubbles grow a certain size before they get sucked in by the measurement pump. Since the FOAM keeps the oil volume in constant circulation with 45 l/min

the gas concentration is almost constant in the reservoir. This can be proven by varying the position of the suction hose. Its end should stay immersed for at least 20 mm to prevent from "slurping" or sucking in surface foam.

3 Test Conditions

Bubbly dispersions with the following gas concentrations (CG) were generated with FOAM in ATF at room temperature and at three additional test temperatures and then captured by means of the microscope:

| Temp. | Set gas concentration "CG-set" | | | | | | | |
|-------|--------------------------------|----------|----------|----------|----------|----------|-----------|-----------|
| 20°C | 0,0 vol% | 0,5 vol% | 1,0 vol% | 2,0 vol% | 5,0 vol% | 7,5 vol% | 10,0 vol% | 20,0 vol% |
| 40°C | 0,0 vol% | 0,5 vol% | 1,0 vol% | 2,0 vol% | 5,0 vol% | 7,5 vol% | 10,0 vol% | 20,0 vol% |
| 80°C | 0,0 vol% | 0,5 vol% | 1,0 vol% | 2,0 vol% | 5,0 vol% | 7,5 vol% | 10,0 vol% | 20,0 vol% |
| 120°C | 0,0 vol% | 0,5 vol% | 1,0 vol% | 2,0 vol% | 5,0 vol% | 7,5 vol% | 10,0 vol% | 20,0 vol% |

Fig.5: Set CGs and test temperatures

4 Test Results

Low flow rates in the measuring line are set up to slow down the flow of the air bubbles and reduce the blur of their silhouette in the pictures. The digital ocular was turned in a 45° angle so that the diameters can be estimated by measurement on the X-axis.

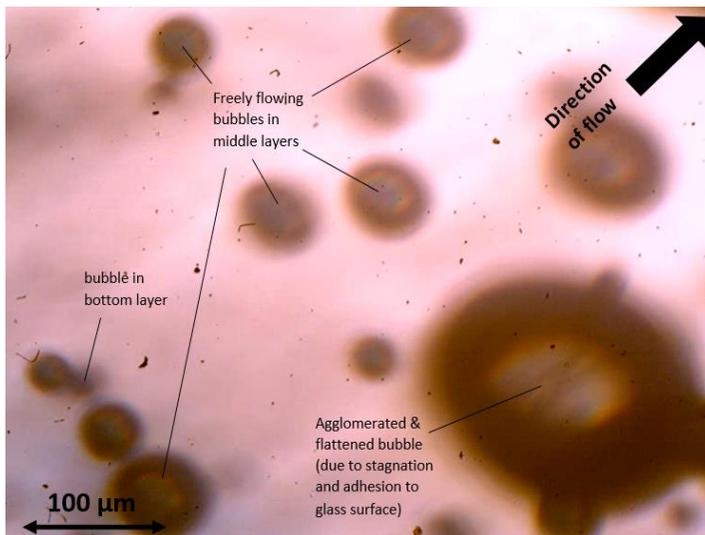


Fig.6: microscopic view on CG = 0,5 vol% in oil @ 80°C (0,5 mm section)

For oil at higher temperatures (approx. > 60°C) bubble agglomeration became visible through some increasingly large bubbles with Ø 100-200 µm in the top layer. This kind of degassing effect is most likely caused by the lower oil viscosities which lead to faster rising speeds of all gas bubbles. Some of them then gain size as they agglomerate, and when flowing so slowly some are pushed up against the glass and flattened. Since they lose their spherical form, measuring their diameter does not give correct information about their volume.

The average diameter of the air bubbles inside the aerated oil was determined by analysis of the findings in four pictures for each CG and temperature combination. **Bubble diameters ranged from approx. 25 to 200 µm**, with the ladder from stagnant agglomerated bubbles, which were not included in the averaging.

Although the air-in-oil dispersions appeared very homogenous another problem was to find the correct diameter of the bubbles in lower fluid layers of the 3 mm thick observed level. These bubbles were blurry and appeared smaller as they were too far below the focused, scaled layer.

Therefore only the focused, freely flowing bubbles in the scaled layer (focal length approx. 3,2 mm) were taken into consideration. They could be identified by their sharp silhouettes.

The resulting values of the diameters found showed constancy for all CGs over the full temperature range.

| AVG DIAM. [µm] @ Temp. | 0,5 vol% | 1,0 vol% | 2,0 vol% | 5,0 vol% | 7,5 vol% | 10,0 vol% | 20,0 vol% |
|------------------------|----------|----------|----------|----------|----------|-----------|-----------|
| 20°C | 65 | 75 | 65 | 60 | 65 | 70 | 95 |
| 40°C | 70 | 75 | 65 | 65 | 70 | 75 | 85 |
| 80°C | 75 | 75 | 70 | 70 | 75 | -- | -- |
| 120°C | 75 | 70 | 75 | 70 | 70 | -- | -- |

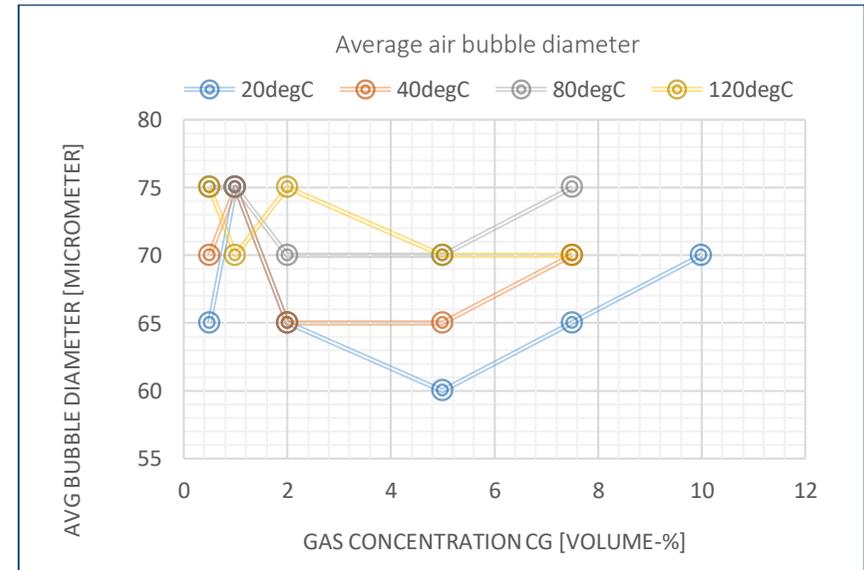


Fig.7: approx. average bubble diameters at atm. pressure for each tested CG/temp.

Higher CGs made it more difficult to inspect the layers below the growing stagnant top layer, while also less of the transmitted-light from the bottom got through. Thus correct measurement could not be conducted (marked in grey on previous page).

Nevertheless the constancy of the diameters over the course of the full test was high, not just for isothermal testing but with a low deviation in the diameter distribution within a range of 50 – 85 μm for all tested temperatures.

The overall **average bubble diameter is 70 μm** , which results in an average bubble volume of approx. 100 μm^3 .

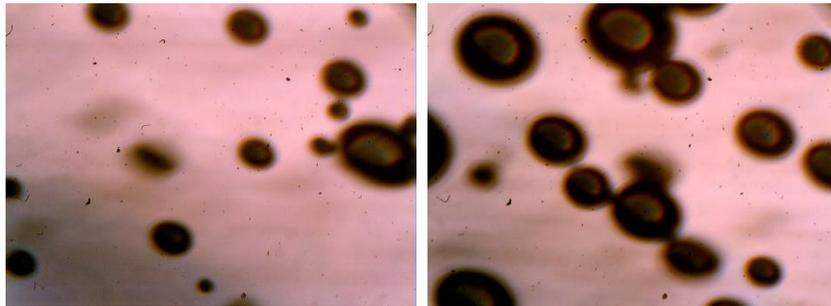


Fig.8: microscopic views on CG = 0,5 vol% (left) and CG = 1,0 vol% (right) in ATF @ 20°C

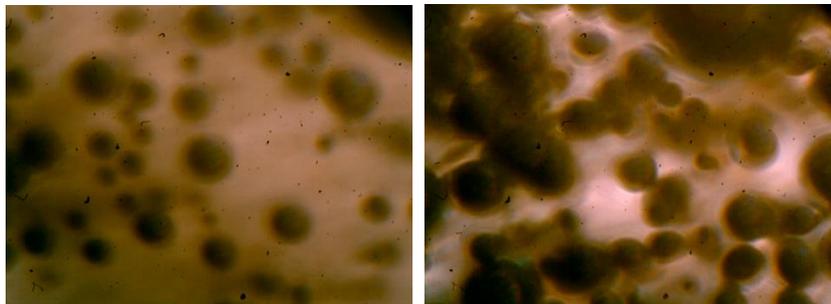


Fig.9: microscopic views on CG = 2,0 vol% (left) and CG = 5,0 vol% (right) in ATF @ 20°C

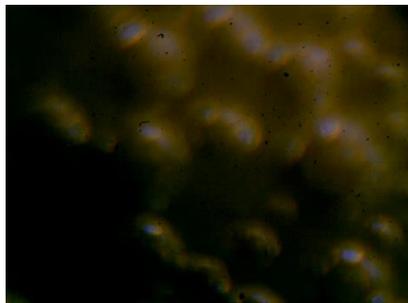


Fig.10: microscopic view on CG = 20,0 vol% in ATF @ 20°C, blocked by surface foam

5 Setup Improvements

For further investigations the sight glass should be designed even thinner to allow fewer fluid layers. Acceleration of the flow would prevent bubble agglomeration but would make it difficult to capture the faster bubbles. A flash and a camera with a faster shutter would improve the picture quality.

6 Conclusions & prospects

It was found that in aerated ATF gas bubble sizes are almost constant for varying temperatures/viscosities and gas concentrations. The average bubble diameter is 70 μm at atmospheric pressure.

Air-in-oil dispersions are volatile mixtures that naturally tend to degas especially when stagnating. In order to prevent bubble agglomeration during optical analysis especially for high CGs the flow rate must be raised and an additional camera with flash light synchronization should be used for higher shutter speeds.

For part 2 further optical investigations should be made on the pressure-dependency of gas-in-oil dispersions. Both CG sensor and sight glass shall be installed on the pressure side of the measuring pump with a ball valve installed on its outlet to be used as a throttle. This is to examine the effects of compression, visualizing both the decrease of the bubble volume and the dissolving of the gas.

Results are expected for September 2019.