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Experimental Techniques to Determine Oil Distribution in Automotive A/C Systems

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ABSTRACT

This paper presents experimental techniques to determine the amount of lubricant in each of the major components of an R134a automotive A/C system using ND-8 (PAG 46) oil—compressor, condenser, liquid tube, evaporator and accumulator. Three different techniques are presented:

- Remove and weigh
- Flushing
- Mix and sample

The advantages and disadvantages, as well as the suitability of each technique are discussed. The uncertainties of each technique applied to different components of the experimental system are presented. Applying these techniques shows that the overall amount of lubricant in the system can be determined with an uncertainty of $\pm 2\text{g}$ which is less than $\pm 1\%$ for the experimental system. In addition, a new method to separate refrigerant and lubricant is presented which does not require a solvent, and allows reusing the lubricant after separation. This method has an accuracy of $\pm 0.04\text{g}$ of refrigerant left in the lubricant after separation.

1. INTRODUCTION

Mineral or synthetic oils are used as lubricants in refrigeration systems primarily to reduce the wear of the moving parts of the compressor. Since it is unavoidable that some lubricant leaves the compressor, lubricant is found throughout the system. Part of the lubricant travels with the refrigerant flow, and this flow can be described as lubricant-in-circulation rate. However, some lubricant can accumulate in the different components of the system and this accumulation has to be taken into account when estimating the amount of lubricant necessary for a certain system. In addition, components need to be designed in a way to reduce the amount of lubricant accumulation and to assure that lubricant can be returned to the compressor. Furthermore, the presence of lubricant changes the thermophysical properties of the refrigerant-lubricant mixture based on the concentration of lubricant in the liquid refrigerant-lubricant mixture. Therefore, it is of interest to determine where and how much lubricant is found in each component.

A state of the art R134a automotive A/C system, utilizing a fixed orifice tube, microchannel condenser, plate and fin evaporator, U-tube type accumulator and fixed displacement compressor, is used to test experimental techniques to determine the lubricant distribution. The system is installed in two environmental chambers and ball valves are installed around the major components: compressor, condenser, liquid tube, evaporator and accumulator. Further information about the system setup and experimental facility can be found in Peuker and Hrnjak (2009). The refrigerant, R134a, and the lubricant, Polyalkylene Glycol (PAG) oil with a viscosity of 46 cSt, are a miscible refrigerant-lubricant combination over a wide range of pressure and temperatures as presented by Seeton and Hrnjak (2009). The uncertainties in this document are based on a 95% level of confidence unless otherwise stated.

2. TECHNIQUE FOR SEPARATION OF REFRIGERANT AND LUBRICANT

The flushing and the mix and sample techniques both involve a sampling vessel containing a mixture of refrigerant and lubricant. Therefore, a technique is necessary to separate the refrigerant from the lubricant in order to determine

the amount of lubricant in a sample. ASHRAE (1996) provides a standard procedure to measure the proportion of lubricant in liquid refrigerant which includes a separation technique. Following the standard an experiment is conducted. A sampling cylinder is filled with 86.82 g \pm 0.02 g PAG 46 oil and then 20.81 g \pm 0.02 g of R134a is added. The sampling cylinder is connected to a pressure calibrator and placed on a scale. A vacuum pump is used, as described by the standard, to evacuate to a pressure of 0.27 kPa. This procedure is repeated four times and the results are shown in Table 1.

Table 1: Mass of R134a left in sampling cylinder after evacuation

Evacuation run	1	2	3	4
Mass of R134a left in cylinder (g)	10.07 \pm 0.02	8.78 \pm 0.02	6.29 \pm 0.02	4.55 \pm 0.02

It should be pointed out that the ASHRAE standard is aimed to determine the concentration of small samples, e.g. for automotive systems the sample cylinder size should be 50 ml or smaller. The sampling cylinder size used for the flushing and the mix and sample techniques is 800 ml and due to the nature of these techniques the lubricant and refrigerant quantities can be of the order of 100 grams. Based on the results presented in Table 1 and knowing that the sampling cylinder size violates the ASHRAE standard a new method has been developed.

Since there will be a significant amount of R134a (>100 g) in a sampling cylinder, the refrigerant is first recovered from it. This is done by placing a recovery cylinder in an ice bath and connecting it to the sampling cylinder. The connection includes a transparent tube directly at the sampling cylinder to assure that only vapor phase refrigerant is leaving the sampling cylinder. Also included is a flow meter to monitor the refrigerant vapor flow. First the valve at the recovery cylinder is opened and then the needle valve of the sampling cylinder is carefully opened to avoid boiling inside the sampling cylinder. Boiling can lead to foaming of the refrigerant lubricant mixture and potentially lubricant could leave the sampling cylinder. If the flow meter indicates that the initial vapor flow has ceased the sampling cylinder is placed in warm water (ca. 40 °C). The sampling cylinder stays connected to the recovery cylinder for one hour. The sampling cylinder is then placed into a hot (ca. 90 °C) water bath and connected to a vacuum pump. The sampling cylinder is evacuated three times for 20 minutes. After each evacuation run the sampling cylinder is placed on a scale to determine its weight and henceforth, knowing the tare weight, the amount of lubricant left in the sampling cylinder can be determined. Comparing the weight of the sampling cylinder after the second and third evacuation is used as a check, the difference in weight should be less than the detection limit. The detection limit results from the measurement uncertainty of the scale used and the uncertainty associated with the determination of the tare weight of the sampling cylinder. In the presented case the detection limit is \pm 0.02 g. Several R134a and PAG 46 lubricant mass combinations, as listed in Table 2, have been tested with the aforementioned procedure.

Table 2: Refrigerant lubricant combinations for verifying separation method

PAG 46 lubricant (g)	R134a (g)	Difference in measured lubricant mass after 2 nd and 3 rd evacuation run (g)
49.58	299.44	
49.67	119.91	
49.70	117.76	<0.04
157.85	466.25	

The results demonstrate that the aforementioned procedure is effective in separating the refrigerant from the lubricant and that the lubricant mass inside a sampling cylinder can be determined within \pm 0.04 g for the equipment used in this investigation.

3. REMOVE AND WEIGH TECHNIQUE

The principle of the remove and weigh method is to remove a section and compare its weight to its tare weight. If this method is used to determine the lubricant mass in a section three uncertainties arise. First, the uncertainty associated with determining the tare weight. Second, the uncertainty due to removing the refrigerant mass especially

if the refrigerant lubricant mixture is miscible. Third, the uncertainty of determining the weight of a section with the lubricant inside. The second uncertainty depends on the method of refrigerant extraction. The first and third uncertainties are related to the scale used. Besides the accuracy of the scale used, other uncertainties might exist, for example, a section cannot be easily placed on a scale, such as a long tube, or the center of mass of the section is at an offset from the geometrical center.

The remove and weigh method is applied to the compressor of the experimental system. The tare weight of the compressor is known with an uncertainty of ± 0.5 g. To determine the uncertainty which is associated with removing the refrigerant from the compressor, the following procedure is used. The refrigerant is recovered from the compressor by using the liquid nitrogen method presented by Peuker and Hrnjak (2009). Then the compressor is connected to a vacuum pump and evacuated for 20 minutes. The weight of the compressor is then determined and the compressor is evacuated again for 20 minutes. This procedure is repeated four times and the results are shown in Table 3.

Table 3: Verification of procedure to extract refrigerant from compressor

Time of vacuum (min)	20	20	20	20	20
Weight compressor (g)	5821.89	5821.45	5821.21	5821.22	5821.20
Difference weight (g)		0.44	0.24	<0.02	<0.02

The weight of the compressor is determined by placing it on a scale and measuring its weight four times, each time rotating it by 90° on the scale. The reported weight is then the average of the four weights with an uncertainty of ± 0.02 g which equals the detection limit. After the third evacuation, as shown in Table 3, the difference in weight is below the detection limit of ± 0.02 g. A fourth evacuation confirms this result and therefore it can be concluded that for the compressor used in this investigation an evacuation time of 60 minutes is sufficient to remove the R134a within ± 0.02 g. The dominant uncertainty of the remove and weigh method applied to the compressor of this investigation is the uncertainty of the tare weight. Therefore, if the tare weight is known precisely this technique has a very small uncertainty, which is primarily limited by the measurement uncertainty of the scale used.

4. FLUSHING TECHNIQUE

The idea of the flushing technique is to use a solvent, which could be a chemical solvent or a refrigerant, and force it through a section so that the solvent removes the lubricant. Capturing the solvent and separating it from the lubricant allows determining the amount of lubricant extracted. This method is used in industry to clean and/or retrofit systems, e.g., Carpenter (1992) and Symonds (1998). For mobile air conditioning systems, SAE standard J2788 (2006) establishes the specific minimum equipment performance requirements for recovery and recycling of R134a. A commercially available recycling device conforming with this standard is not only able to recover R134a, but also to flush a section. The recycling device fills a section with liquid phase R134a, circulates the R134a and lubricant mixture, recovers the mixture, and then separates the lubricant and purges it into a vessel. Experimenting with such a commercial recycling device demonstrated that it is effective in removing lubricant from a section. However, it was found that the amount of lubricant purged from the recycling device after one flushing run did not match the amount of lubricant filled in. It is found that the uncertainty in using the recycling device to measure the lubricant content is ± 15 g for more than 100 g of lubricant in a section and ± 5 g for less than 100 g of lubricant in a section.

To lower the uncertainty, a manual flushing method, using R134a as a flushing agent, is used to determine the amount of lubricant in the accumulator section of the breadboard system. The geometry of the automotive accumulator, however, makes the application of a flushing method challenging since the accumulator is designed to separate liquid and vapor effectively. In addition, it only allows vapor and a small fraction of liquid—entrained through the oil bleeding hole at the bottom of the U-tube—to leave the accumulator. Therefore, during a flushing procedure, in which the accumulator is first completely filled with R134a, and then R134a is recovered, a significant amount of R134a can be recovered by evaporation only, leaving some lubricant behind. Therefore, several flushing runs are necessary because only a fraction of the lubricant is removed with each flushing run. To overcome this problem an outlet was installed at the bottom of the accumulator. After the accumulator section is isolated by closing the ball valves, a sampling cylinder chilled in liquid nitrogen is connected to the outlet at the bottom of the

accumulator. The liquid refrigerant lubricant mixture is then drained into the sampling cylinder and after separation of lubricant and R134a, the amount of lubricant can be determined (this is referred to as the 1st flush). However, some lubricant remains in the accumulator. Therefore, the accumulator is flushed through two times with pure liquid R134a, one time from the outlet side (2nd flush) and one time from the inlet side (3rd flush) directly into a liquid nitrogen chilled sampling cylinder connected to the outlet at the bottom of the accumulator. Verification experiments are performed to determine the uncertainty associated with this method. The accumulator is filled with a known quantity of first lubricant and then R134a, with and without giving the refrigerant and lubricant time to diffuse. To achieve a homogeneous mixture the R134a and lubricant remained in the accumulator for at least 15 hours. For the inhomogeneous case the flushing method is initiated directly after the R134a is filled in. Overall six experiments are conducted for each case. The accumulator is filled with 100 g of lubricant and 300 g of R134a before the first flushing procedure is initiated. Table 4 summarizes the result of these experiments.

Table 4: Results of experiments to validate flushing technique

Flush	Inhomogeneous mixture	Homogenous mixture
	Lubricant remaining after flushing (g)	Lubricant remaining after flushing (g)
1 st	6.18±2.37	5.42±2.15
2 nd	2.49±1.34	1.94±0.79
3 rd	1.97±1.16	1.43±0.61

As it can be seen, extracting the refrigerant lubricant mixture through the bottom outlet of the accumulator (1st flush) leaves more than 5 g of lubricant behind and justifying the additional two flushes. More flushes most likely would remove even more lubricant from the section, but considering the tradeoff between better results and time commitment necessary, three flushes are considered sufficient. Therefore, the accuracy of determining the amount of lubricant in the accumulator section is 1.43 g±0.61 g for a homogenous mixture and 1.97 g±1.16 g for an inhomogeneous mixture.

5. MIX AND SAMPLE TECHNIQUE

Based on the previously described techniques the remove and weigh technique would give the most accurate results if applied to the heat exchangers, assuming the tare weight is known to a high degree of accuracy and the refrigerant is removed effectively. However, dirt accumulating on the heat exchanger over time, water condensate on the evaporator, and removing a heat exchanger from a system are some issues making the remove and weigh technique challenging. Therefore, an in situ technique to determine the amount of lubricant within a section is being used, based on a method developed by Wujek *et al.* (2010).

The general idea is to exploit the miscibility of the R134a and PAG lubricant combination by filling a section completely with liquid R134a. After the refrigerant diffuses with the lubricant and forms a homogeneous mixture a sample is taken and the concentration of lubricant in the sample, $\omega_{lub,s}$, is determined. By assuming that the concentration of the sample is identical to the concentration in the section, $\omega_{lub,sec}$, the total amount of lubricant in the section, $m_{lub,sec}$, can be calculated using equation (1) if the amount of refrigerant in the section, $m_{R134a,total}$, is known.

$$\omega_{lub,s} = \omega_{lub,sec} = \frac{m_{lub,s}}{m_{lub,s} + m_{R134a,total}} \rightarrow m_{lub,sec} = \frac{m_{R134a,total} \omega_{lub,s}}{1 - \omega_{lub,s}} \quad (1)$$

Equation (1) requires a homogeneous mixture of refrigerant and lubricant. By just filling a section with liquid refrigerant it can take several hours until a homogenous mixture is achieved. To enhance the mixing and shorten the time it takes to perform a measurement a mix and sampling device (MSD) was built. This device has, besides a gear pump to circulate the liquid refrigerant and lubricant mixture, several additional features as shown in Figure 1. One feature is a volume added by a tank to provide an additional space for better mixing of the refrigerant and lubricant mixture. The additional tank doubles as a gas separator. A transparent tube parallel to the volume allows the liquid level within the volume when a sample is taken to be monitored. An additional transparent tube is connected directly to the sampling cylinder to monitor if flashing (separation of liquid and vapor) occurs upstream of the sampling

cylinder. The charge port at the top of the device allows charging of the MSD and an attached section with R134a. The device is mounted on a frame making it portable and easy to install close to a section.

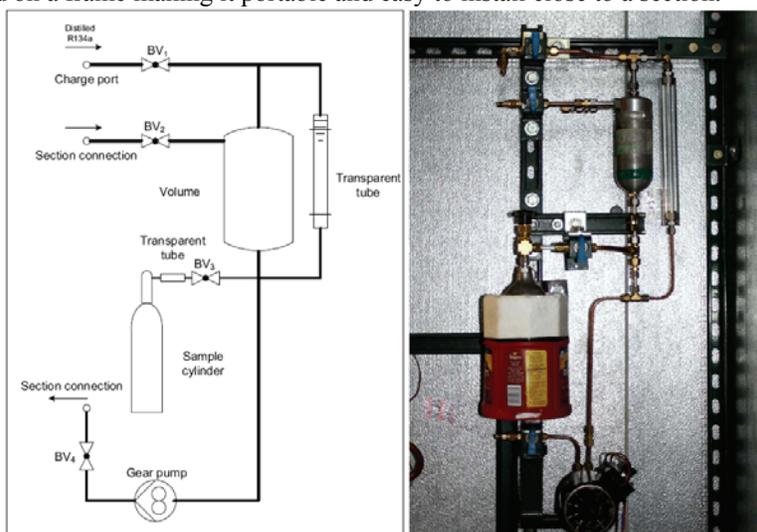


Figure 1: Schematic and picture of mix and sampling device

Acetone is used to clean the device after each use to avoid that leftover lubricant spoils the next measurement. For this cleaning procedure the two ports which usually are connected to a section are short circuited with a tube. Acetone is filled into the device through the charge port and is circulated with the gear pump for two minutes. The acetone is drained and the device is evacuated to remove any leftover acetone. This procedure is repeated twice and measurements confirm that less than 0.04 g of lubricant remains within the device after this cleaning procedure.

The procedure to measure the amount of oil contained within a section starts after the refrigerant is removed from the section. After the evacuated and cleaned device is connected to a section, liquid R134a with a purity of at least 99.6% is filled into the device from a recovery cylinder. The temperature of the recovery cylinder is maintained well above room temperature and the filling is done slowly enough so that the filled-in R134a increases the temperature in the section. This is done to avoid evaporation of the liquid R134a which would occur if the surface temperatures in the section would be higher than the filled in R134a. Since a small increase in temperature leads to a large change in pressure for saturated liquid R134a, the device and attached section is not completely filled with liquid R134a. The filling procedure is stopped when a small amount of vapor is still visible at the top of the transparent tube next to the tank. After the filling procedure, the recovery tank is disconnected and its weight and henceforth the amount of R134a filled into the device and section is determined. The gear pump is turned on and left running for 60 minutes. To take a sample, the sampling cylinder is cooled with liquid nitrogen and the ball valve, BV_3 , is slowly opened such that no flashing is visible in the transparent tube. Depending on the sample size, the sampling will take minutes. After the sampling is finished, the sampling cylinder is removed and the amount of lubricant in the sample is determined by the separation technique described in section 2.

The amount of lubricant in a section cannot be calculated based on equation (1) because of the way the MSD is being used. Two corrections are necessary. First, when filling the clean device the tube between ball valve (BV_3) and the tee below the tank will be filled with liquid R134a. It is assumed that this volume stays filled with liquid R134a, e.g., no measurable amount of lubricant will diffuse into this tube, and therefore this amount, $m_{R134a,tube}$, will be forced into the sampling cylinder at the beginning of the sampling process. Equation (2) shows that the mass of R134a in the tube can be calculated based on the saturated liquid density as a function of temperature, $\rho_{R134a,sat,liq}$, and the volume of the tube, V_{tube} .

$$m_{R134a,tube} = \rho_{R134a,sat,liq}(T) \cdot V_{tube} \quad (2)$$

Second, since the sampling procedure takes place over several minutes vapor will be generated within the device and section. This release of R134a from the liquid phase into the vapor phase changes the concentration of the lubricant in the liquid refrigerant and lubricant mixture. Therefore, the lubricant concentration of the sampled liquid

mixture changes over time. To account for this change the final lubricant concentration of the sample, $\omega_{\text{lub},s}$, is taken as the average of the concentrations at the start of the sampling, $\omega_{\text{lub},t0}$, and at the end of the sampling, $\omega_{\text{lub},t1}$. The assumption of a linear change of lubricant concentration with time is made in equation (3).

$$\omega_{\text{lub},s} = \frac{\omega_{\text{lub},t0} + \omega_{\text{lub},t1}}{2} \quad (3)$$

The concentration of lubricant in the sample can also be expressed in terms of the mass of lubricant in the sample, $m_{\text{lub},s}$, mass of R134a and lubricant in the sample, $m_{\text{total},s}$, and the correction for the mass of R134a in the short tube, $m_{\text{R134a,tube}}$, as shown in equation (4).

$$\omega_{\text{lub},s} = \frac{m_{\text{lub},s}}{m_{\text{total},s} - m_{\text{R134a,tube}}} \quad (4)$$

The mass of R134a released from the liquid phase into the vapor phase during sampling, $m_{\text{R134a,vap}}$, can be calculated by assuming that the mass of R134a in the sample at the end of the sampling, $m_{\text{R134a,s}}$, created a volume inside the device and section which is then occupied by R134a saturated vapor. Evaluating the specific densities for saturated vapor and saturated liquid based on the temperature during the sampling process, $v_{\text{R134a,sat,vap}}$, and $v_{\text{R134a,sat,liq}}$, the amount of $m_{\text{R134a,vap}}$ can be determined by equation (5).

$$m_{\text{R134a,vap}} \cdot v_{\text{R134a,sat,vap}}(T) = m_{\text{R134a,s}} \cdot v_{\text{R134a,sat,liq}}(T) \quad (5)$$

The equations for the lubricant concentrations at the beginning, $\omega_{\text{lub},t0}$, and at the end, $\omega_{\text{lub},t1}$, are shown in equation (6) and (7).

$$\omega_{\text{lub},t0} = \frac{m_{\text{lub,sec}}}{m_{\text{lub,sec}} + m_{\text{R134a,total}} - m_{\text{R134a,tube}}} \quad (6)$$

$$\omega_{\text{lub},t1} = \frac{m_{\text{lub,sec}} - m_{\text{lub},s}}{m_{\text{lub,sec}} - m_{\text{lub},s} + m_{\text{R134a,total}} - m_{\text{R134a,tube}} - m_{\text{R134a,s}} - m_{\text{R134a,vap}}} \quad (7)$$

Solving equations (2) through (7) determines the mass of lubricant within the section of interest, $m_{\text{lub,sec}}$.

To verify the uncertainty associated with the MSD itself, the device is short-circuited with a refrigerant hose to perform verification experiments. Before each experiment the MSD and the refrigerant hose are cleaned. The refrigerant hose is filled with a measured amount of lubricant. The MSD is then run based on the procedure described previously and the predicted amount of lubricant is calculated based on equations (2) through (7). The predicted amount of lubricant is compared to the amount of lubricant filled in, the difference between these values is the uncertainty. Table 5 shows the results of the verifications experiments. As it can be seen using only equation (1) results in considerable error. Accounting for the measurement uncertainties from using the scales and temperature measurements, it can be concluded that the amount of oil within the device can be determined with an uncertainty of ± 0.08 g if equations (2) through (7) are used.

Table 5: Results of the verification experiments of the MSD

Amount of oil in MSD (g)	Calculation of lubricant based on equations (2) to (7) (g)	Difference (g)	Calculation of lubricant based on equation (1) (g)	Difference (g)
20.57±0.06	20.51±0.08	-0.06	19.93±0.08	0.58
19.58±0.06	19.60±0.08	0.02	18.97±0.08	0.63
20.70±0.06	20.66±0.08	-0.04	20.04±0.08	0.62

Although the MSD produces a homogeneous mixture when short-circuited, the question remains how well a homogeneous mixture can be achieved when the MSD is applied to the liquid tube, condenser and evaporator

sections. Therefore, three verification experiments are performed on the liquid tube and the condenser sections, and five experiments on the evaporator section. For the verification experiments each section is cleaned first, a known amount of lubricant is then filled into the section after which the MSD is connected to the section. Table 6 presents the average difference and standard deviation between the filled-in mass of lubricant and the estimation based on the mix and sampling technique using the MSD and equations (2) to (7).

Table 6: Uncertainty of mix and sampling technique per section

Liquid tube (g)	Condenser (g)	Evaporator (g)
0.10±0.35	-0.22±0.36	-0.42±0.35

A positive or negative difference between the predicted and known value of lubricant indicates an inhomogeneous mixture. A negative difference, as observed for the condenser and evaporator, could indicate that the refrigerant did not mix with all the lubricant, e.g., one or several “dead spots” exist where lubricant remains unmixed. However, overall the difference between known amount of lubricant and predicted amount using the MSD technique is less than 1 g for all sections.

6. SUMMARY

Table 7 shows an overview of the techniques and their uncertainties used on each section of the automotive breadboard system.

Table 7: Overview of techniques used by sections

Section	Compressor	Condenser	Liquid Tube	Evaporator	Accumulator
Technique	Remove and Weigh	Mix and Sample	Mix and Sample	Mix and Sample	Flushing
Uncertainty (g)	±0.06 g	-0.22±0.36	0.10±0.35	-0.42±0.35	1.43±0.61

Using the three presented techniques, 13 experiments are conducted to measure the overall mass of lubricant in the breadboard system. For each experiment the amount of lubricant inside the system ranges from 229.19 g to 232.29 g whereas the uncertainty of the filled in amount of lubricant is ±0.06 g. Since this uncertainty is an order of magnitude lower than the uncertainties associated with the flushing and mix and sample techniques, the filled in amount is taken as the actual value. For each experiment the actual mass of lubricant in the system is compared to the sum of masses of the lubricant determined by applying the three techniques. The results are presented in Figure 2. Based on the verification experiments on each section, the combined expected deviation from the actual mass of lubricant in the system is $-0.9 \text{ g} \pm 1.73 \text{ g}$, where the range results from propagating the measurement uncertainties. As Figure 2 shows, 11 out of 13 measurements fall within that range and the mean value of all measurements, -1.2 g, is close to the expected value. Therefore, it can be concluded that the application of the presented techniques to determine the lubricant mass within the experimental system can be determined with an uncertainty of ±2g which is less than ±1% in terms of the total lubricant mass in the system.

7. CONCLUSIONS

Based on the discussions presented, the mix and sample technique is recommended to determine the lubricant mass inside heat exchangers and can potentially used on any component except the compressor. For the latter, the remove and weigh technique is recommended. The flushing technique can be used on any component, except the compressor, but as a result of the separation of lubricant from the solvent during recovering, requiring several flushing runs, this method can be time consuming. For the presented study the remove and weigh technique (not accounting for the uncertainty related to the tare weigh) has the least uncertainty followed by the mix and sample and the flushing technique. Since it is necessary to separate refrigerant from lubricant for both, the mix and sample and flushing techniques, a new method to separate R134a and PAG 46 oil is presented. This method has an accuracy of ±0.04g of refrigerant left in the lubricant after separation and allows reusing the lubricant after separation.

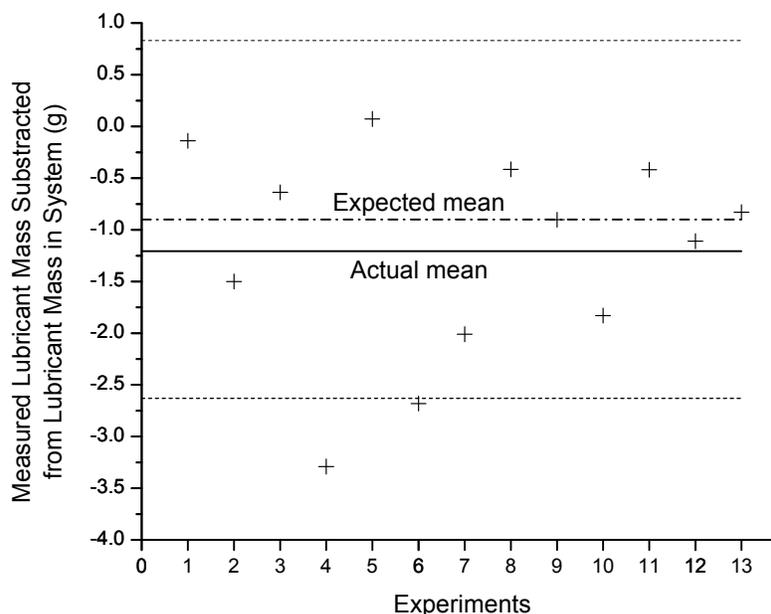


Figure 2: Comparison between measured and actual lubricant mass in the system

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