An approach to optimize the design of hydraulic reservoirs

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Abstract

Increasing demands regarding performance, safety and environmental compatibility of hydraulic mobile machines in combination with rising cost pressures create a growing need for specialized optimization of hydraulic systems; particularly with regard to hydraulic reservoirs. In addition to the secondary function of cooling the oil, two main functions of the hydraulic reservoir are oil storage and de-aeration of the hydraulic oil. While designing hydraulic reservoirs regarding oil storage is quite simple, the design regarding de-aeration can be quite difficult. The author presents an approach to a system optimization of hydraulic reservoirs which combines experimental and numerical techniques to resolve some challenges facing hydraulic tank design. Specialized numerical tools are used in order to characterize the de-aeration performance of hydraulic tanks. Further the simulation of heat transfer is used to study the cooling function of hydraulic tank systems with particular attention to plastic tank solutions. To accompany the numerical tools, experimental test rigs have been built up to validate the simulation results and to provide additional insight into the design and optimization of hydraulic tanks which will be presented as well.

KEYWORDS: Hydraulic reservoirs, filter-tank system, numerical optimization, experiment, simulation, de-aeration performance, degassing function, heat transfer

1. Introduction

A basic function of hydraulic reservoirs in mobile applications is the storage of oil. Most of the mobile machines are equipped with differential cylinders which have a variable fluid capacity. In consequence of the cylinder operation the oil volume in the tank varies. The oil volume in the tank also changes as a conclusion of the thermal expansion of the oil during the warm-up of the machine. In addition to this variable amount of oil stored in the tank there is always a fixed amount of oil. This is necessary to ensure the degassing of the free air in the oil. The source of the air will be explained in the following.

Henry's law describes the amount of air VG that can be solved in a defined volume of hydraulic oil VFl at a specific pressure /1/.

$$V_G = V_{Fl} \cdot \alpha_V \cdot \frac{p}{p_0} \qquad (1)$$

For mineral oils in balanced condition at atmospheric pressure p_0 approximately seven percent by volume is in solution. Due to local pressure drops in the suction lines of pumps as well as due to jet streams especially in hydraulic valves the amount of air that can be solved according Henry's law is reduced proportionally to the pressure. As a consequence free air in form of air bubbles is present. A further source of air ingression to the oil is the sloshing of the oil in the tank. There is a big spectrum of bubble diameters in the range of approximately 1 µm and 5 mm. In some cases the bubble diameter can be even bigger when air is deposited in the hydraulic system.

The free air in hydraulic systems causes degradation of the oil as a conclusion of oxidation. Furthermore due to the compression of the air bubbles high temperatures can occur which also damages the oil. A further consequence of this effect is the reduction of the overall efficiency of the hydraulic pumps and therefore an increase in fuel consumption. Due to the increased compressibility the handling and control of the hydraulic systems also can decline.

Degassing bubbles of free air in the hydraulic tank is a complex function and is depending on many influencing factors. Increasing the amount of fixed oil in the tank generally improves the degassing function. An optimization of the design of hydraulic tanks in regard of the de-aeration performance allows improving the degassing function without increasing the amount of oil or even in combination with a reduction of the tank size. As manufacturer of mobile machines are strongly driven by a big cost pressure due to global competition as well as packaging issues mainly due to changes in legislation the interest in optimizing hydraulic reservoirs is very high. Concrete guidelines how to optimize tank systems are still missing and have to be worked out.

As the return filter which is normally mounted into the tank is essentially influencing the degassing function in the following the term filter-tank system will be used.

A further function of the tank is the reduction of the oil temperature due to heat transfer to the environment. This property is especially very interesting for smaller machines. In some applications an improvement of the tank design even allows the elimination of the main cooler.

2. Experimental characterization of hydraulic reservoirs

In order to be able to optimize hydraulic tank systems a characterization of the degassing function is necessary. An experimental approach will be described. Furthermore a test setup to determine the heat transfer of tank systems will be shown.

2.1. De-aeration performance

In order to characterize the de-aeration performance of hydraulic reservoirs a test setup for hydraulic filter-tank systems was build up. Furthermore to be able to measure the amount of free air in hydraulic systems a sensor was developed which is able to measure the amount of free air in the oil.

2.1.1. Air Content Sensor

In order to characterize and optimize hydraulic reservoirs regarding de-aeration performance the content of free air in hydraulic fluids has to be determined. For this purpose a special sensor was developed. The sensor is based on the electric capacitive principle. The effective dielectric constant of the fluid in the capacitor defines the capacity of the capacitor. While oil has a dielectric constant of approximately 2.7 air has a value of approximately 1. An increased amount on free air in the oil will reduce the capacity of the capacitor and can thereby be used for quantification. Because of the dependency of the dielectric constant with the temperature a compensation of the measurement result has to be performed. The sensor as well as the test setup will be introduced in the following.

2.1.2. Test setup

Figure 1 shows the hydraulic schematics of the test setup.

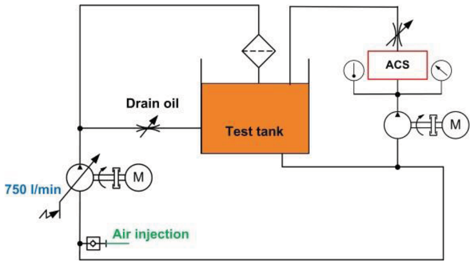

Figure 1: Test setup

The volume flow through the tank is regulated using a variable pump. Using a special nozzle in combination with a mass flow controller air is injected to the suction line in a defined way. The Air Content Sensor (ACS) is used to measure the air content in the suction line with a sampling rate of one Hz. **Figure 2** shows an exemplary measurement result comparing two different tank concepts.

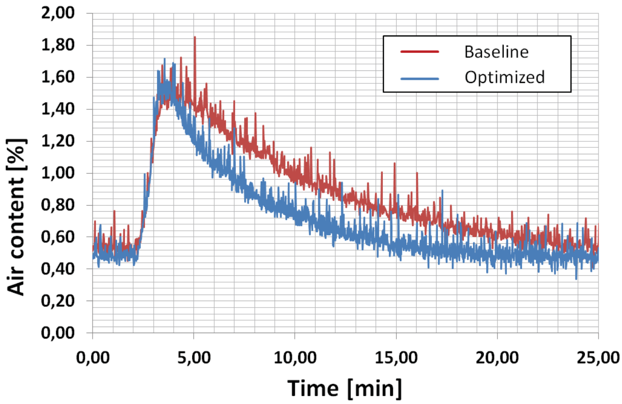

Figure 2: Measurement results

One percent of air is injected at the point two minutes for the duration of one minute. Looking at the transient air content it is obvious that the de-aeration performance of the optimized filter-tank system is on a better level.

The test rig with the special Air Content Sensor allows a characterization of tank systems regarding de-aeration performance. It allows a comparison of different tank designs and can be used to validate optimizations evaluated using simulation tools.

2.2. Heat transfer

In order to quantify the cooling function of tank systems a wind tunnel test was performed. The hydraulic reservoir is placed inside the wind tunnel and is equipped with several thermocouples measuring the temperature of tank, air and oil. The hydraulic system is mounted on the outside of the tunnel in order to avoid disturbances. **Figure 3** shows the tank placed inside the tunnel.

Figure 3: Test tank in wind tunnel

At the inlet of the wind tunnel on the opposite of the fan drive the velocity field was measured. The result of the flow field during the test is shown in **Figure 4**.

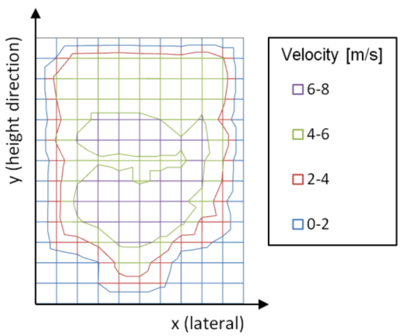

Figure 4: Velocity profile at wind tunnel inlet

This measurement allows the calculation of the total volume flow through the tunnel as an input value for the simulation model. The temperature of the oil in the tank was used in order to determine the heat transfer. Before starting the fan drive the oil was heated up to 60°C. Afterwards the oil flow through the tank was stopped. **Figure 5** shows the profile of the oil temperature measured during the test time.

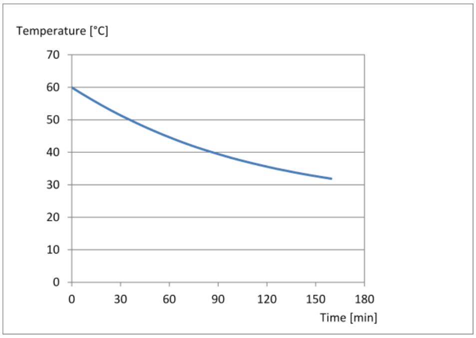

Figure 5: Oil temperature during measurement

This measurement profile will be used in chapter 3.2. in order to validate the results from simulation.

3. Simulation of hydraulic reservoirs

In the following an approach to determine the de-aeration performance of hydraulic filter-tank systems is shown. Furthermore the results of a thermal heat transfer simulation will be shown and will be compared to the experimental results shown in chapter 2.2.

3.1. De-aeration performance

A multi-phase bubble flow simulation can be used to calculate the de-aeration performance of filter-tank systems. Bubbles with different sizes in diameter are injected to the return line. The term simulated de-aeration performance which is used in the following is defined as the number of bubbles de-aerated inside the tank in relation to the number of bubbles injected to the tank. It has to be noted that this value is dependent on the bubble size. **Figure 6** shows two simulation results done for the two different tank systems which were used in chapter 2.1.2.

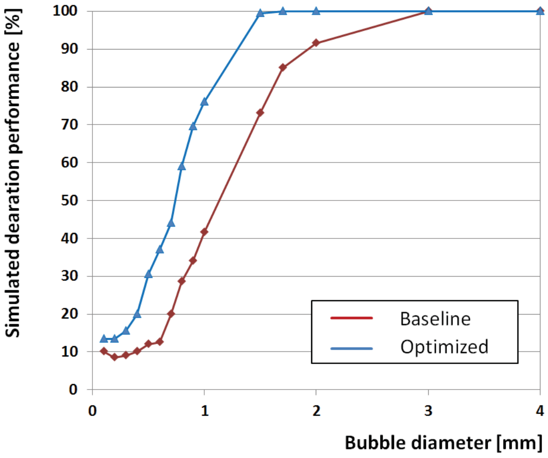

Figure 6: Simulated de-aeration performance

This approach can be used to optimize hydraulic tank systems. Nevertheless an experimental validation as shown in chapter 2.1.2 is strongly recommended.

3.2. Heat transfer

In the following a comparison of the results from the heat transfer simulation with the experimental investigations shown in chapter 2.2. is shown. **Figure 7** shows the simulated velocity profile during the test.

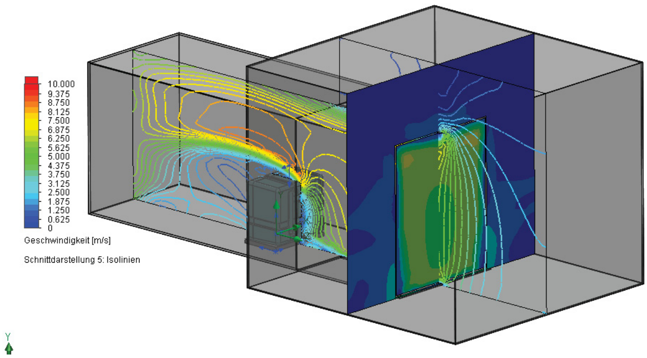

Figure 7: Simulation results velocity profile

The volume flow at the fan drive as a boundary condition was adjusted to a value that fits the simulated volume flow at the tunnel inlet to the measured flow. **Figure 8** shows the simulated heat transfer density at the surface of the tank. It can be observed, that the heat transfer at the upper level of the tank where air is present is on a much lower level as at the part where the tank is filled with oil.

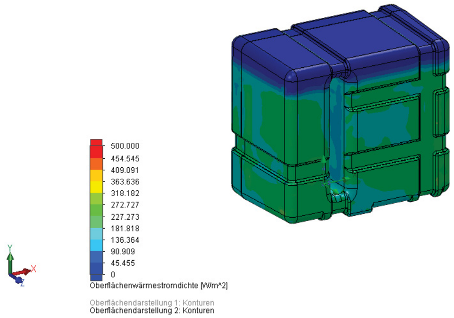

Figure 8: Heat transfer density at outer tank surface for 60°C oil temperature

An integration of the heat transfer density over the tank surface gives the overall heat transfer. **Figure 9** shows a comparison of measurement and simulation.

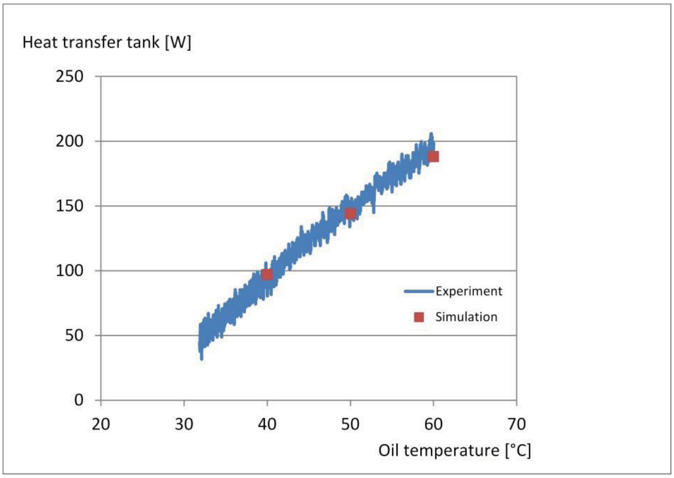

Figure 9: Comparison simulation and experiment

It can be seen that the simulated results are qualitatively as well as quantitatively in a very good agreement with the measurement. It can be concluded that the usage of thermal simulations to determine heat transfer at tank systems is quite accurate.

4. Summary

One of the main functions of hydraulic reservoirs is degassing the free air. The amount of oil inside the tank is only secondarily accountable for the degassing performance. Primarily it is the design of the inner tank geometry as well as the type and position of the filter. Because of the lack of knowledge in the design of tanks many hydraulic reservoirs are still sized in a very conservative way. Optimizing the design of hydraulic filter-reservoir systems allows a reduction of the tank size. This allows a significant cost reduction as well as improving the package of components on mobile machines.

By usage of an experimental setup which contains a sensor to measure the amount of free air the degassing performance of filter-reservoir systems can be determined. The usage of multi-phase bubble flow simulation tools allows a computer aided optimization. Nevertheless an experimental validation is always strongly recommended.

A secondary function of hydraulic reservoirs is the cooling of the oil due to heat transfer to the environment. A quantitative analysis helps to dimension the cooling circuit of the system. A comparison with experimental results has shown that the results from a thermal simulation are quite accurate and therefore very useful to be used for the dimensioning of the cooling circuit.

5. References

/1/ Murrenhoff, 2012, Grundlagen der Fluidtechnik, Auflage 7, Shaker Verlag.

6. Nomenclature

α_V	Bunsen coefficient	-
p	Pressure	bar
p_0	Athmospheric pressure	bar
V_G	Volume of air	m³
V_{Fl}	Volume of fluid	m³