HOLISTIC EFFICIENCY MEASUREMENTS OF A MOBILE WORKING MACHINE: COMPARISON OF CONVENTIONAL MINERAL OILS AND A SUSTAINABLE WATER-BASED FLUID

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ABSTRACT

The selection of pressure fluids plays an important role in hydraulic systems' efficiency. Depending on physical properties, especially the viscosity, different volumetric and hydraulic-mechanical losses occur in the system. This paper investigates the influence of hydraulic fluids with different physical properties on a crawler excavator's energy efficiency. For this purpose, the overall efficiency of the excavator is examined for different mineral oils and an alternative water-based fluid with deviating viscosity classes and indexes. The study results show that reducing the energy demand over a wide temperature range by lowering the viscosity grade or increasing the viscosity index is not generally feasible. To reduce losses by adapting the hydraulic fluid in a hydraulic system further physical and chemical properties such as pressure viscosity behaviour as well as the density must be considered.

Keywords: Efficiency measurement, Sustainable fluid, Excavator, Dig and dump, Viscosity, Viscosity Index, Water-based fluids, Viscosity improver

1. INTRODUCTION

Reducing greenhouse gas emissions is one of the main concerns regarding sustainable environmental and climate protection. Legally, the reduction is regulated by the Paris Climate Agreement [1]. In Germany, greenhouse gas emissions must be reduced by 95 % by 2050 compared to 1990. Globally, mobile machines are responsible for 1 % of total CO_2 emissions [2].

Optimizing the efficiency of hydraulic systems plays a decisive role. As shown in [3], major efficiency improvements can be achieved by adapting the hydraulic system´s architecture. This leads to a corresponding reduction in fuel consumption and consequently, to a reduction in greenhouse gas emissions. Further efficiency improvements can be reached by adaptation to the hydraulic systems components. The main attention concerning research activities is paid to improving hydraulic pump efficiency. Axial piston pumps are often part of the research work, because of their widespread usage [4, 5]. In addition to friction and volumetric losses in tribological contacts of hydraulic displacement units, power losses in hydraulic systems mainly occur due to pressure losses in pipes or components such as valves [6, 7]. An approach of today's research activities to reduce pressure losses in hydraulic components and flow paths is optimizing flow geometries [8–10]. Furthermore, research activities already exist to determine the influence of hydraulic fluids and their physical properties on the efficiency of hydraulic components [11] and elementary hydraulic systems [12].

In this paper, the influence of hydraulic fluids with different physical properties on the energy efficiency of a crawler excavator will be investigated. Therefore, the overall efficiency of the excavator is examined for different mineral oils and an alternative fluid with deviating viscosity classes and indexes. For this reason, hydraulic fluids are tested while executing an automated dig and dump cycle at different temperature stages. With this method, it is possible to compare and analyse

the efficiency of the excavator while using different hydraulic fluids. The research can be related to the investigations in [13]. The test excavator of the previous research was adapted to optimize the reproducibility as well as the accuracy of the measurements. The conventional drive unit, the diesel engine, was replaced by an external electronic drive unit. Furthermore, it is possible to temper the tank volume of the hydraulic unit as well as to record the drive power directly via torque measurements instead of fuel consumption measurements.
The paper is structured as follows: First, the state of the art is presented concerning the loss mechanism that occurs in hydraulic systems, divided into hydraulic mechanical losses and volumetric losses. After that, the losses are assigned to components that are used in the excavators' hydraulic system. Furthermore, the influence of the hydraulic fluid's physical properties on the loss mechanism is discussed. The state of the art is concluded with a presentation of the different viscosity behaviour of various base fluids used in this study concerning relevant operating parameters regarding temperature and pressure. The third chapter deals with the testing setup of the investigations. The excavator and its hydraulic system architecture are presented. Afterwards, the testing cycle is explained. Chapter three concludes with a presentation of the hydraulic fluids investigated. In the following chapter, the evaluation of the tests is discussed. For this purpose, different aspects are considered, such as energy consumption and temperatures when using the different fluids as well as the characteristics of different types of losses in the hydraulic system. The paper concludes with a summary of the results and an outlook on future research aspects.

2. STATE OF THE ART

The following chapter deals with the fundamentals of losses in hydraulic systems and their components. Therefore, first, the loss mechanisms in hydraulic systems are presented followed by the classification of these losses to specific components of hydraulic systems. The chapter is completed by the description of the viscosity behavior of different base oils, which have great significance on loss characteristics.

2.1. Loss mechanisms

According to [14], the power loss P_{loss} in an hydraulic system results from the input power P_{in} generated by the hydraulic pump and the total efficiency η_{total} of the hydraulic system (1).

$$P_{loss} = P_{in} \cdot (1 - \eta_{total}) \tag{1}$$

Energy losses in hydraulic systems result in the dissipation of heat energy to the hydraulic fluid. This leads to an increase in fluid temperature and corresponds to a decrease in viscosity. Based on the hydraulic system of mobile machines, energy losses in the system can be assigned to corresponding system components. Mainly, the losses occur in pumps/motors, valves and pipe/hose lines. Further losses occur, for example, in coolers or filters. The energy losses appear in superimposed form during the operation of the machine.

Hydraulic-mechanical losses

Hydraulic-mechanical losses occur in the form of friction losses in tribological contacts of hydraulic components. In these contacts, such as the piston/bushing contact of an axial piston pump, the separation of the surfaces of contact partners moving relative to each other is achieved by a hydrodynamic lubricating film. This lubricating film bears the load arising at the contact and separates the friction partners, in the best case, completely from each other. If the viscosity of the lubricants drops to such an extent that the separation of the surfaces can no longer be guaranteed, the load-bearing lubricating film can no longer be formed, and the contact is driven in boundary lubricating conditions. The influence of varying pressure-viscosity behavior of different base oils on the formation of load-bearing lubricating films and the friction conditions in tribological contacts has been experimentally investigated in [15]. Consequently, friction in hydraulic-mechanical losses increase the lower the dependency of pressure on fluids viscosity.

Volumetric losses

Volumetric losses are defined in terms of volumetric loss flow that occurs functionally in hydraulic displacement units. Compression losses as well as internal and external leakage lead to volumetric losses. In hydraulic pumps and motors, internal leakage occurs because of a compensating volumetric flow from the high-pressure to a low-pressure side in function-related gaps. These volumetric losses occur for example, in the annular gap of a piston/bushing contact of an axial piston pump. The flow in this region is mostly laminar and can be described by Hagen-Poiseuille´s law [16]. Hagen-Poiseuille is an equation that connects the pressure drop and the volumetric flow rate with the hydraulic resistance. With an increase in viscosity, the volumetric losses decrease.

2.2. Hydraulic system losses

The architecture of a hydraulic system has a decisive influence on the efficiency of a mobile machine. In [7], the occurring losses during a 90° dig and dump cycle using a crawler excavator were determined experimentally. The losses of the individual hydraulic system components were considered based on the energy input of the fuel. 20 digging cycles were carried out by a test driver and the measurements were averaged. It was shown that about 7.4 % of the input energy could be converted into useful energy for the operation. Around a quarter of the losses can be attributed to the hydraulic system. In addition to system-related losses due to control tasks (such as load-sensing architecture), losses occur in flow guides like hoses, valves and pumps as well as motors. These losses are dependent on the viscosity of the fluid used. The influence of viscosity on different types of losses is possible due to the complexity and overlapping of losses by forming balance boundaries and will be examined in more detail in this paper. For this purpose, different aspects of the viscosity behavior of different base oils as well as different temperature-viscosity behavior will be considered.

2.3. Viscosity behaviour of different base oils

Viscosity generally describes the internal resistance against the shearing of a liquid. It is used as a measure of the internal friction of a liquid. This internal friction occurs between the molecules of a flowing medium [17]. Molecular chains slide on top of each other due to an initiated force.

The viscosity of lubricants generally depends on various parameters such as shear, temperature, and pressure. For mineral oils and synthetic oils with comparable molecular dimensions, Newtonian behaviour of the fluids can be assumed for relevant shear rates in hydraulic systems. Therefore, viscosity is shear-independent. The investigations done for this paper focus on the viscosity-temperature behaviour and viscosity-pressure behaviour.

Lubricants viscosity generally decreases with increasing temperature. The amount of the influence of temperature on viscosity is numerically described by the so-called viscosity index (VI). The higher the VI the lower the influence of temperature change on the lubricant’s viscosity. A temperature-stable viscosity favours the prediction of lubricant behaviour in systems concerning different operation temperatures. Furthermore, it lowers the fluid-dependent frictional losses for example while starting a system at low ambient temperature. The viscosity dependency of lubricant primary can be referred to the chemical structure of the base oil. Long carbon chains with only a few branches lie very near to each other and interfere with each other if the temperature rises and the molecules oscillate (e.g., synthetic oils and water-glycol). Otherwise, in mineral oil based lubricants the gaps between the chains are larger because of for example aromatic cyclic bounds. Thus, there are few contact points between the molecules since the hydrocarbon chains are spatially separated from each

other by cyclic structures. This gap increases as the temperature rises and the chains straighten. Therefore, the VI of synthetic oils and water-based fluids is higher than that of mineral oil based fluids.
By adding so-called viscosity improvers, the VI of mineral oils (HVLP [18]) can be brought to the same value as that of esters or polyalphaolefins. For this purpose, used polymers are formed as a coil at low temperatures and by rising temperatures they expand and fill the gaps between the hydrocarbon chains. In contrast to the base oils, the long chains are prone to shear stress. The chains can be cut, and as a result, they lose their viscosity-improving effect. Similar behaviour can be seen at HFC [19] fluids where polymers are used to achieve the needed viscosity. [20, 21]
The pressure-viscosity dependency is described by the pressure viscosity coefficient α. Pressure-viscosity dependency can be explained by taking a closer look at the chemical structure of base fluids. The more side branches fluids have the more the viscosity depends on pressure. If the (hydrocarbon) chains are pressed closer together the branches interlock with each other and build a further resistance against sliding between the chains. As already mentioned, mineral oils consist of a more branched structure like synthetic and water-based fluids. For this reason, their viscosity dependency on pressure is higher. The pressure dependency is important for the formation of load-bearing lubricant films in tribological contacts, for example in hydraulic pumps. Due to a high dependency of lubricant viscosity on pressure, the fluid can form more stable lubricating films. The pressure-dependent viscosity η_p can be explained by the exponential approach of Barus (2) [22]. The viscosity η_0 is obtained at a defined temperature under atmospheric pressure.

$$\eta_p = \eta_0 \cdot \exp(\alpha \cdot p) \tag{2}$$

3. TESTING SETUP

In the following chapter, the testing setup of the research is presented. Therefore, the crawler excavator and its hydraulic system are explained and followed by the integration of the hydraulic unit that drives the excavator. The sensor accuracies are shown to classify the reliability of the results. Next, the testing cycle is shown. After that, the investigated hydraulic fluids and their relevant properties for this study are explained.

3.1. Testing Excavator

The crawler excavator belongs to the class of compact excavators, and it is driven by tracks. In addition to linear actuators, which are required for digging, there also are actuators for further operations which are not regarded in the investigations. The test excavator is controlled by electro-hydraulic pilot valves instead of the usually implemented hydraulic joysticks. The pump of the excavator is pressure-controlled. The total weight of the machine is 1,790 kg. The gross power of the diesel engine is 12 kW. The nominal bucket filling level is 36 liters. The hydraulic tank consists of 15 liters and its complete hydraulic system capacity is 21 liters. The test excavator is equipped with appropriate measurement technology to record relevant data. The right side of **Figure 1** shows the main circuit of the hydraulic system with installed sensors. The main circuit consists of three linear actuators which are the boom (9), arm (8), and bucket (6) cylinders. The swivel motor (1) correspondingly drives the slewing gear for swiveling the upper carriage. The diesel engine drives the main hydraulic pump. Other actuators, such as the track motor, are not considered in this study because they are not activated during the executed test cycle.
Regarding the existing hydraulic drive system of the excavator (black box), the transferred power of the combustion engine to the shaft of the hydraulic pump can only be evaluated via fuel consumption. This measurement method only allows limited statements about the mechanical input power of the hydraulic pump. The reason for that is unknown parameters, such as the efficiency of the combustion

engine. Therefore, the conventional drive system of the excavator (black box) was replaced and an external hydraulic power supply (red box) was adapted to drive the excavator. The circuit diagram of the combined hydraulic system consisting of the hydraulic unit and excavator's hydraulic system (blue box) is shown in **Figure 1**. The pressure line of the power unit is connected to the hydraulic system of the excavator immediately after the pump of the excavator. The return line is discharged in front of the excavator´s internal cooler and filter. The throttle is needed to regulate the pressure of the pump. To calculate the input energy of the electric motor torque and rotation speed is measured. Furthermore, the pressure and temperature of the pressure line are identified as well as the leakage oil temperature and tank temperature. The tank temperature can be kept constant at the set value via a controlled air cooler. Heating is done while throttling the fluid by a pressure relief valve.

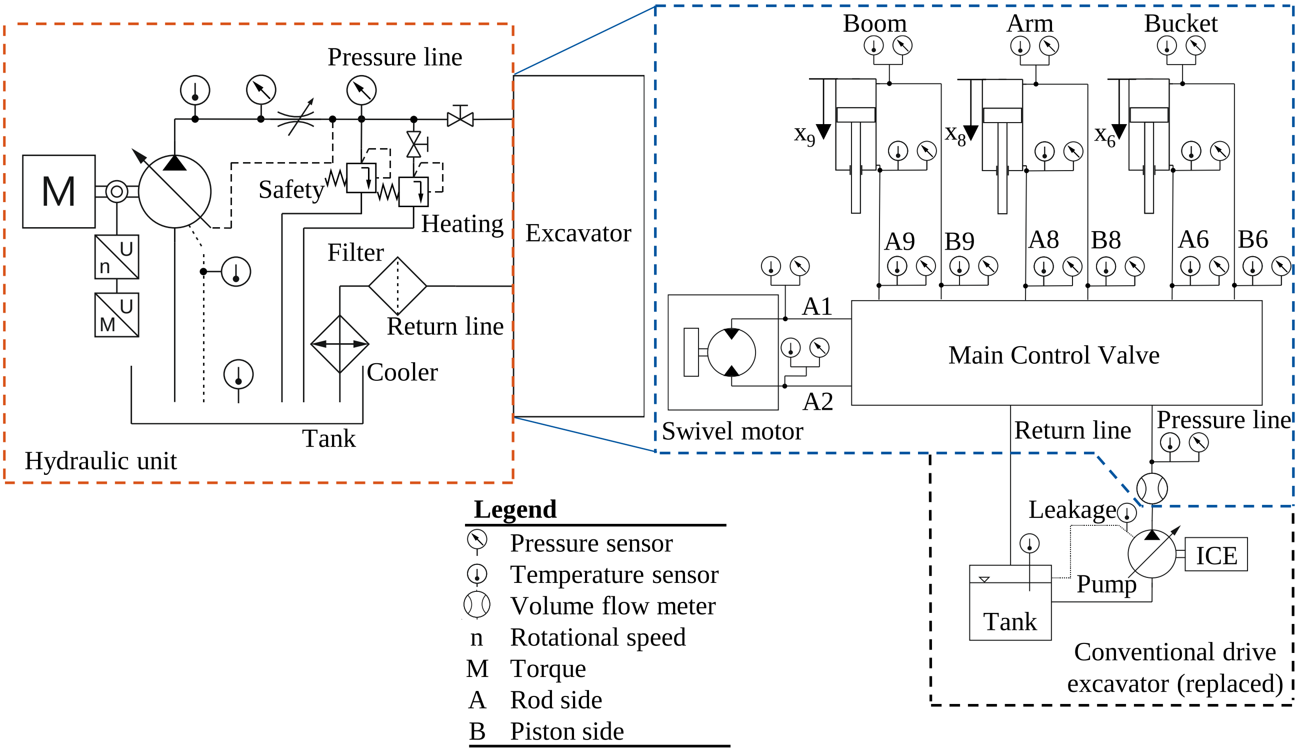

Figure 1: Hydraulic system excavator and hydraulic unit

3.2. Accuracy

In **Table 1** the measurement range and corresponding accuracy of the sensors used are shown. The accuracy refers to the measurement range of the sensors. The sensors' positioning in the excavator's hydraulic system is shown in **Figure 1**. For temperature measurement thermocouples of type K according to DIN EN 60584-1 [23] are used whose measuring range according to class 1 is -40 °C to 1,000 °C. Referring to the standard, the permissible limit deviation is 1 °C. All sensors are calibrated concerning their entire measurement chain regarding their measurement range during application.

Table 1: Sensor accuracy

Sensor type	Range	Accuracy
Pressure	0 … 250 bar	+/- 0.5 %
Volume flow	1 … 150 l/min	+/- 0.2 %
Torque	0 … 500 Nm	+/- 0.03 %
Rotational speed	0 … 500 rpm	+/- 0.04 %
Length	0 … 2,000 mm	+/- 0.001 %

3.3. Automated dig and dump cycle

The typical construction site activity of an excavator consists of the sum of different load cycles. The main task is the load cycle “digging” with 40 % [24]. The executed test cycle is based on test cycles defined by the Japan Construction Mechanization Association (JCMA) [25] for determining the energy consumption and energy losses of hydraulic excavators. A 90-degree dig and dump cycle is performed as a test cycle. The duration of the cycle is about 58 seconds.

The execution of the cycle is shown in **Figure 2**, and the time concerning the start of the cycle is also described. Instead of digging material, a weight (25 kg) is attached to the bucket and moved during the digging cycle. The weight does not leave the bucket during the cycle. Beginning from the start position, the excavator performs a digging movement after which it is guided back to the starting position (0-25 sec). The upper carriage is then swivelled by 90° (25-32 sec) and the excavator performs an emptying movement (32-44 sec). Finally, the arm is moved back to the starting position and the upper carriage is swivelled back (44-end). The whole movement is automated. An electro-hydraulic prototype control allows completely automated and reproducible digging cycles. For this purpose, a dig and dump cycle was run manually and the respective cylinder lengths as well as the upper carriage rotation were recorded. These data were stored in the control system in a look-up table, which contains the respective lengths of the actuators over time. After starting the implemented automatic dig and dump program, the lengths are fed into a controller, which actuates the slide position of the valves belonging to the actuators. With this automatization, the cylinder lengths and the rotational angle are controlled. For this, reason the output energy is comparable for different fluids. Thus, it is possible to perform a completely automated and reproducible 90° dig and dump cycle allowing to compare different fluids with various physical properties regarding their performance.

Section	**Process**
1	Digging movement 0 - 25 sec
2	Rotation upper carriage 25 - 32 sec
3	Unload movement 32 - 44 sec
4	Rotation to starting position 44 sec - end

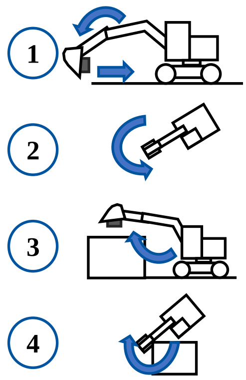

Figure 2: Dig and dump cycle

3.4. Hydraulic fluids

Three hydraulic fluids with different physical properties are part of the investigations. The most important properties regarding the investigations are shown in **Table 2**.

The first hydraulic fluid studied is a mineral oil based hydraulic oil with a viscosity class of 46. This is a frequently used hydraulic oil in various industries and mobile applications. Therefore, in this study, the HLP [26] is used as a reference fluid concerning the results. The second fluid is a mineral oil based fluid with the same paraffinic base oil type as the HLP, but it is concentrated with viscosity improvers (HVLP [18]). The lower viscosity class of 32 is chosen to specify if it is possible to reduce the energy consumption of the mobile machinery when reducing the overall viscosity of the hydraulic fluid. The higher VI is necessary to fulfil the minimum viscosity requirements of the pump at high temperatures. The third hydraulic fluid is based on a mixture of water and glycol (HFC [19]); its viscosity class is 46. Due to the high measurement effort related to the investigations in the study, only three fluids could be investigated. The water content of the investigated HFC is about 40 %. The water-based hydraulic fluid is chosen as a representative of alternative and sustainable hydraulic fluids. In comparison to mineral oils, it reduces the impact of fossil-based carbon on the environment. Furthermore, it is over 90 % biodegradable within 28 days (OECD 301 [27]) and reduces the environmental impact of spilling hydraulic fluids. Accidents of mobile machinery play a decisive role concerning hydraulic oil spills [28]. Additionally, the HFC fluid has a high VI comparable to those of other sustainable biobased oils (e.g., ester).

For changing the fluids, a flushing process was done. The previously used fluid was drained, and the system was filled with the fluid to be tested. The actuators of the excavator were then moved to flush residual oil out of the system. This procedure was repeated until the hydraulic fluid represented the required purity demanded by ISO 15380 [29].

Table 2: Important properties tested hydraulic fluids [20, 21, 30, 31]

Hydraulic fluid	Viscosity class [32]	Viscosity index [33]	Density [g/cm³] (20 °C)	Specific heat capacity [kJ/(kg K)]	Thermal conductivity [W/(m K)]	Pressure Viscosity Coefficient [(GPa)$^{-1}$] (25 °C)
HLP	46	113	0.86	1.9–2.2	0.13–0.14	20.0
HVLP	32	195	0.85	1.9–2.2	0.13–0.14	20.0
HFC	46	206	1.08	3.3	0.3–0.43	2.0

Figure 3 shows the dependence of the hydraulic fluids' dynamic viscosity considered on temperature (a) and pressure (b). The different viscosity indexes of the fluids result in an intersection for HLP and HVLP, which is at about 100 °C outside the area relevant to this study. Between HFC and HLP, there is an intersection at 22 °C and 97 mPas. The viscosity curve of HFC ends at 60 °C because this is the limit of the application range of the water-based fluid. When considering the pressure dependence of the viscosity (b), the relatively low viscosity increase of HFC compared to the mineral oil can be identified, which is particularly important for high pressures in tribological contacts. At low pressures (>200 bar), the resulting deviations in viscosity are relatively small.

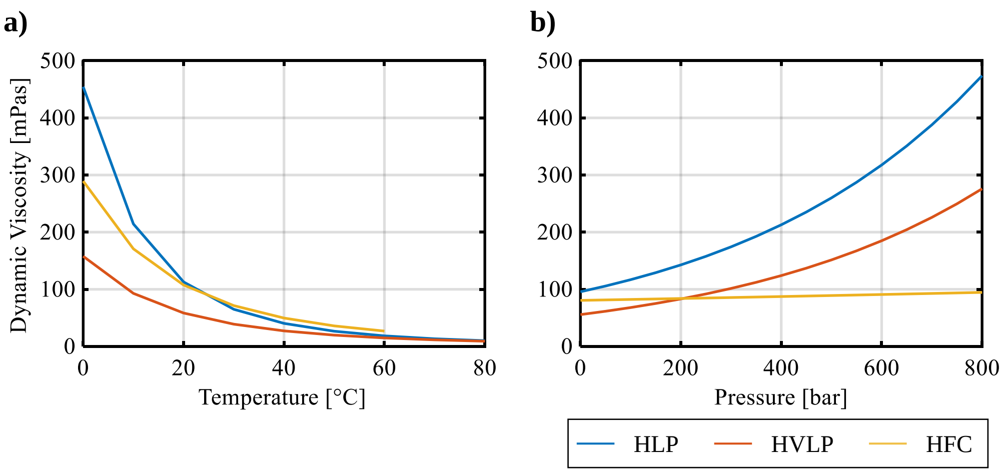

Figure 3: a) Temperature viscosity behaviour and b) Pressure viscosity behaviour investigated fluids

3.5. Testing temperatures

Tests were carried out at three different tank temperatures (**Table 3**). Due to different tank temperatures, it is possible to determine the influence of different viscosities during the operation on the efficiency of the excavator. The first stage is at a tank temperature of 25 °C ± 2 °C to simulate the losses that occur during a cold start of the machine or in operation at low ambient temperatures. The

second stage is at 40 °C ± 2 °C. The third is when the tank has been warmed up and a nearly stationary temperature is reached. Under normal loads, a steady-state tank temperature of 50 °C ± 2 °C is reached during operation at ambient temperatures of 20 °C ± 2 °C.
To achieve statistical accuracy, all measurement values were averaged over 50 cycles at each tank temperature stage for each oil.

Table 3: Testing temperatures

Temperature stage	Range
1	25 °C ± 2 °C
2	40 °C ± 2 °C
3	50 °C± 2 °C

4. MEASUREMENT RESULTS AND DISCUSSION

In this chapter, the measurement results of the excavator tests are shown. After that results of important measurements regarding the comparison of the different hydraulic fluids considered in the study are presented. First, the temperatures at important measurement locations of the hydraulic system are shown. To state the total energy consumption of the different hydraulic fluids the torque measurements are established as well as the presentation of energy consumption during the dig and dump cycle. All measurement data shown refer to the arithmetic average of 50 dig and dump cycles performed for each fluid at every temperature stage (Table 3). Overall, for each fluid, 150 cycles were performed.

4.1. Temperatures

The fluid temperatures during the operation of the excavator depend on the losses in the hydraulic system. The absorption and storage of heat energy by the lubricant are generally dependent on its thermal capacity.
In **Figure 4**, the tank temperature (a) and the leakage oil temperature of the main pump (b) are plotted over the cycle time. The plots are divided into three different temperature stages shown in **Table 3**.
The first row (a) shows the tank temperature over the cycle time. The maximum deviation of ± 2 °C from the respective reference temperature dependent on the stage can be observed. At stages 2 and 3, the tank temperatures are very similar (ΔT_{max}=0.2 °C). Whereas for temperature stage 1 the maximum deviation is 2 °C between HLP and HFC. At this temperature stage, cooling is done by adding an external heat exchanger to the system. The cooling of the coolant is done externally, and its temperature is not held at a constant value. Therefore, the coolant temperatures may differ between the measurements. Nevertheless, the deviations shown are within the previously defined tolerance range (**Table 3**).
The leakage oil temperature (b) indicates the heat development in the pump due to friction in tribological contacts and leakage volume flow. According to the dig and dump cycle progression (**Figure 2**), it can be observed that the maximum temperature increase takes place during the digging process. Especially during the relatively slow movements of digging and the retraction of the bucket, considering the whole cycle, a significant increase in temperature and a temperature peak occurs (t=21 s). This peak is more significant at stages 2 and 3 than at stage 1. This can be described by the increasing leakage flows with increasing temperature and decreasing fluid viscosity.
When considering the temperature difference between the three different hydraulic fluids, it can be noticed that the water-based HFC shows a lower leakage oil temperature than the mineral oil based fluids (HLP, HVLP). This trend can be seen over the entire cycle time and for all temperature stages.

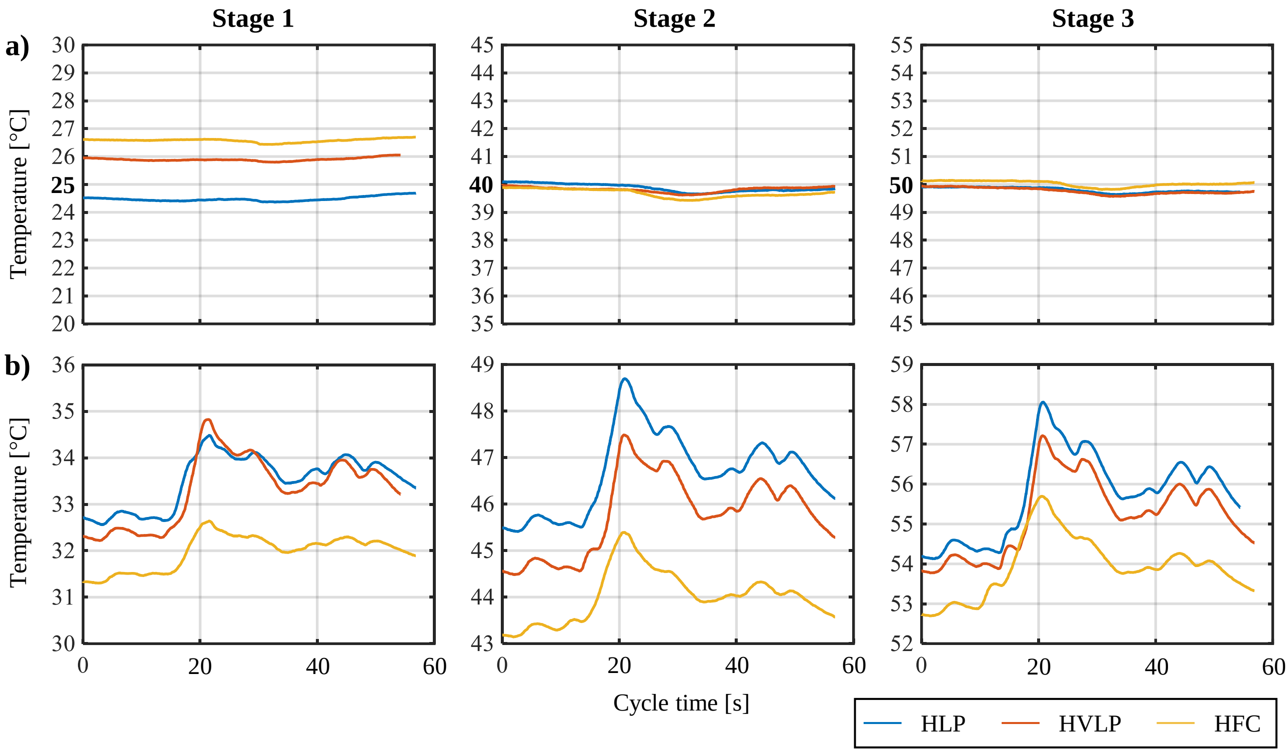

Figure 4: Temperature behaviour over cycle time. a) Tank temperature b) Leakage oil temperature

4.2. Torque and energy consumption

The torque is measured at the shaft between the electric motor and the hydraulic pump. Due to the constant rotational speed (1,500 rpm), it is proportional to the input power. Therefore, the torque can be used to determine, via the cycle time at which operation of the dig and dump cycle the corresponding amount of power is needed. **Figure 5** shows the torque curve over the cycle time for the different temperature stages and hydraulic fluids. In general, it can be concluded that the torque decreases for all fluids as the input temperature increases and the viscosity consequently decreases. Furthermore, the torque when using HFC is higher than when using the mineral oil based fluids at all temperature stages over nearly the entire dig and dump cycle. This is even though the viscosity at stage 1 is lower than that of the HLP (**Table 2**). One exception is the section when the excavator is performing a digging process (t=18-20 s). The low cylinder speeds in this process result in a lower torque when using HFC than with the mineral oil based fluids. An explanation for this behaviour is part of current investigations.

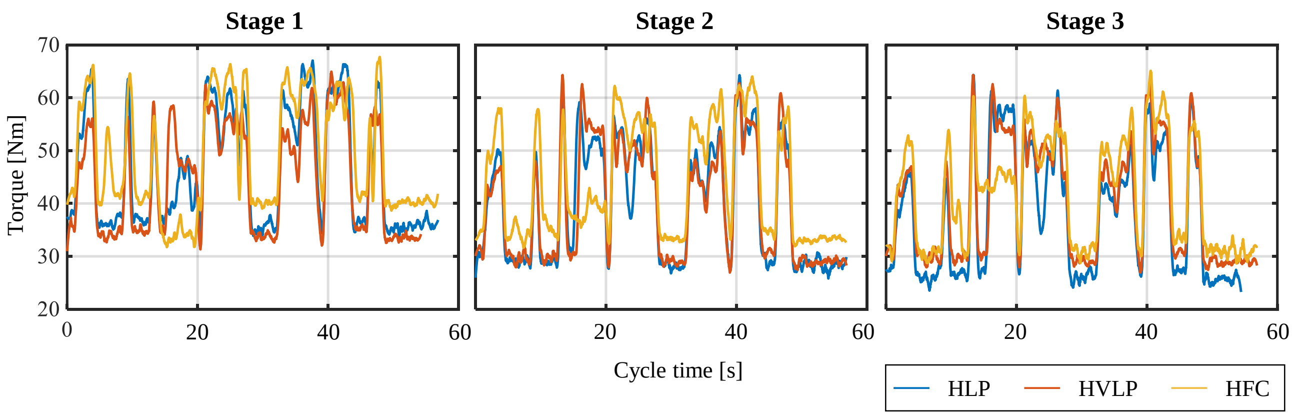

Figure 5: Input torque of different temperature stages

By integrating the power from the multiplication of torque and speed over the cycle time, the energy required to perform the dig and dump cycle can be determined. **Figure 6** shows the energy consumption per average of 50 cycles in kilojoules. The standard deviations for energy and temperature are shown for 50 cycles. The data points between the measured temperature stages are identified by linear interpolation.
The plotted measurement data show that the energy requirement to fulfill the dig and dump cycle is higher when using HFC than when using mineral oil based hydraulic fluids. Furthermore, an intersection between HLP and HVLP can be seen, which can be explained by the different viscosity-temperature behaviour of the oils. In addition, the energy drop over temperature is lower for the two fluids with high VI than for HLP. When considering the standard deviations for energy, these are higher for HLP, than for the other fluids considered. Since the standard deviations for temperature are comparable for all three, it is assumed that this can be linked to the lower VI since the deviations in viscosity are higher in this respect at slightly fluctuating temperatures. At the first temperature stage, the standard deviations for temperature are smaller than for the other temperature stages, this is due to the additional constant cooling power of the additional heat exchanger (see 4.1).
The higher energy requirement when using HFC can be described on the one hand by higher flow losses caused by its higher dynamic viscosity compared to the mineral oil according to the Hagen-Poiseuille law (see chapter 2.1). On the other hand, due to the lower dependence of viscosity on pressure, higher friction losses may occur in tribological contacts, thus increasing the hydraulic mechanical losses. To qualify this assumption, further qualitative investigations are necessary regarding the losses occurring in the pump.

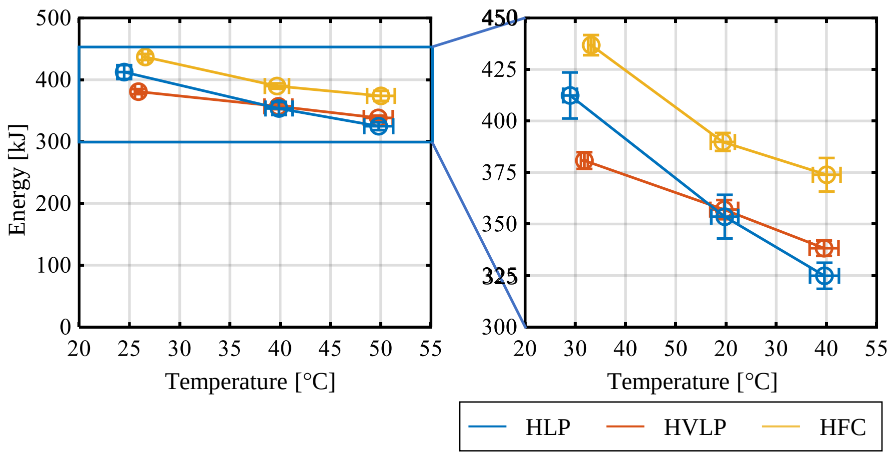

Figure 6: Energy consumption dig and dump cycle

5. CONCLUSION AND OUTLOOK

The research results of this study show different effects in terms of efficiency as well as temperature distribution when using different commercial hydraulic fluids in the excavator. The water-based HFC shows lower temperatures in the leakage oil port of the pump. Explanations can be referred to different thermal properties or a lower leakage oil flow concerning reduced volumetric losses. Further investigations to prove these assumptions are part of current investigations. Regarding energy consumption, the viscosity dependence between HLP 46 and HVLP 32 can be identified. In the low-temperature range (25-40 °C), the energy requirement is below that of HLP, with an intersection at around 40 °C, whereby in the range from 40 °C up to 50 °C, HLP has the lowest energy requirement. The intersection of the kinematic viscosities of the two oils, however, is at a significantly higher temperature of around 100 °C. The energy requirement when using HFC is significantly higher than when using HLP (Stage 1: 5.5 %/Stage 2: 9.3 %/Stage 3: 13.1 %) and HVLP

(Stage 1: 12.8 %/Stage 2: 8.4 %/Stage 3: 9.5 %) at all temperature stages.
In summary, the simplified use of low viscous fluids in hydraulic systems does not necessarily lead to a reduction in energy consumption. This requires a more detailed understanding of the system as well as the identification of losses and the temperature balance of the system. The three commercially available hydraulic fluids show different behaviours regarding these aspects. Especially for fluids with alternative base fluids that are not mineral oil based (e.g., water, ester), the effects on different types of losses must be known here due to their different physical and chemical properties.
Future research work will deal with the subject of dividing losses occurring in the excavator's hydraulic system. Therefore, the segments of the excavator's hydraulic system will be divided into balance sheet boundaries and losses in these segments will be calculated. With this method, it will be possible to evaluate in which area of the system which number of losses occur when using different fluids at different temperature stages. Furthermore, biobased hydraulic fluids (esters) will be included in the considerations.

NOMENCLATURE

P_{loss}	Dissipation power	W
P_{in}	Input power	W
η_{total}	Total efficiency	-
η	Dynamic viscosity	mPas
p	Pressure	bar
α	Pressure-viscosity-coefficient	GPa^{-1}

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