

Influence of differently viscous hydraulic fluid on the flow behaviour inside a hydraulic tank

IGNACIJO BILUŠ, LUKA LEŠNIK, LUKA KEVORKIJAN & DARKO LOVREC

Abstract The viscosity of a hydraulic fluid is certainly one of the most important material properties of a fluid, as it affects a whole range of phenomena in the hydraulic system and the operation of the entire system. Among other things, it affects the efficiency of the hydraulic device directly. Thus, the development of hydraulic fluids goes in the direction of fluids with lower viscosity, which, in turn, results in different flow behaviour and processes inside the hydraulic tank. The paper presents the results of a study of the flow conditions in a small hydraulic tank for cases of different fluid viscosities. The results were obtained based on a detailed simulation of conditions inside the tank. Apart from the impact of the changed flow conditions, the lower viscosity of the liquid also influences the elimination of solid contaminants and air.

Keywords: • hydraulic tank • mineral oil • viscosity • flow condition • simulation •

CORRESPONDENCE ADDRESS: Ignacijo Biluš, University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia, e-mail: ignacijo.blus@um.si. Luka Lešnik, University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia, e-mail: luka.lesnik@um.si. Luka Kevorkijan, University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia, e-mail: luka.kevorkijan@um.si. Darko Lovrec, Prof., University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia, e-mail: darko.lovrec@um.si.

1 Introduction

The hydraulic fluid is a key component of any hydraulic system. It transmits power, lubricates components, dissipates heat and thus cools the components, acts as a sealing agent and helps minimise the harmful effects of contamination like dirt and water. Hydraulic fluid has become increasingly important when it comes to overall system efficiency.

Requirements for today's hydraulic fluids arise from trends in the development of hydraulic components and systems, as well as from operating conditions, taking into account operating trends [1]:

- Higher operating pressures: Typical operating pressures for hydraulic equipment are up to 350 bar or 450 bar.
- Smaller and lighter components: Reduced fluid volume and, consequently, increased flow rates and more intensive circulation and, therefore, less residence time for cooling and elimination of contaminants.
- Higher fluid operating temperatures: In some cases 80 °C, common for mobile hydraulics with more than 100 °C peak temperature, or low ambient temperatures.
- A wider operating temperature range.
- Increasing energy efficiency of the plant, including structural components` design, implementation of energy-saving control concepts, and use of energy-efficient hydraulic fluids with excellent lubricating properties over the wide operating temperature range.

The fluid and components of the hydraulic system must always be considered as an interacting whole. Together they determine the system efficiency and lifetime. The critical elements of a hydraulic fluid are the fluid type and its viscosity. A hydraulic system that operates with an inappropriately selected fluid relative to the component will show weaknesses in:

- changed flow conditions,
- decreased efficiency,
- lack of lubrication,
- reduced components` lifetime,

- corrosion, sludge and varnish,
- heat generation.

Most of the mentioned requirements and possible negative consequences thus refer to the properties of hydraulic fluids, especially those related to the viscosity of the fluid. The fluid must have the appropriate viscosity on the one hand, and additionally, this should be, as little as possible, dependent on the temperature on the other. The influence of the viscosity on the operation and performance of the hydraulic system is shown in Figure 1.

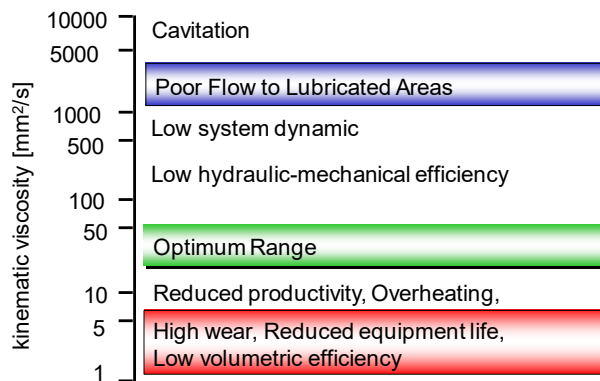


Figure 1: Importance of fluid viscosity within a hydraulic system [2].

Although various fluid properties have an impact on different performance functions, the viscosity is a key material property of the hydraulic fluid that affects the performance and efficiency of the hydraulic components and the entire system. The fluid viscosity affects hydraulic systems in several ways, for example on:

- value of volumetric efficiency,
- value of mechanical efficiency
- (elasto)hydrodynamic and boundary lubrication,
- risk of cavitation,
- heat dissipation,
- Air release ability,
- filterability...

Given all the above, the viscosity of a hydraulic fluid is certainly that material property of the fluid that deserves priority attention. Also, due to the fact that selection of suitable viscosity is related closely to the efficiency of operation of the individual hydraulic components and the overall system. In the present study, the numerical simulation of flow conditions inside a hydraulic tank was performed for three mineral based hydraulic oils with different viscosities. The results were compared and their influence on tank "performance" was analysed.

2 Viscosity and system efficiency

In hydraulic systems much of the energy input is lost in the pumps, fluid lines and actuators. As stated by the manufacturers and researchers of energy-saving hydraulic fluids, in a case of selected inappropriate viscosity and an inappropriately designed hydraulic system, only around 40 % of input energy is available to perform work – Figure 2 (e. g. [3], [4], [5]). In the end, this is reflected in higher electricity consumption, or higher fuel consumption in the case of mobile hydraulics.

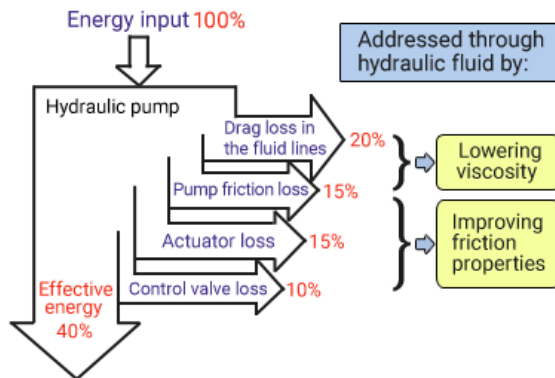


Figure 2: Shares of energy lost [3].

If the selected hydraulic oil viscosity is too low the oil film will be too thin, causing direct metal to metal contact, which leads to excessive wear on components. Low viscous hydraulic oils also increase the risk of internal leakages generating a lower volumetric efficiency of hydraulic pumps and motors. It also leads to overheating, high wear and shorter component life. If the oil viscosity is too high, the system will suffer from slow dynamics, poor flow to lubricated areas and reduced mechanical efficiency. This generates energy losses and

unnecessary heat generation. Other negative effects of a high oil viscosity are cavitation, poor air release and inadequate lubrication, and, in the worst case, mechanical failure.

Losses inside hydraulic components (and accordingly efficiencies), can, therefore, be divided into two main groups:

- hydraulic-mechanical losses – energy loss due to fluid friction, as a resistance of the motion of the component parts in the fluid itself, non-stationary flow condition, which is reflected in lower available force on the actuator,
- volumetric losses – energy loss as the result of internal leakage within all component parts with gaps: Pumps, valves, hydromotors, which is reflected in lower actuator speed.

In order to maximise energy efficiencies in hydraulic systems, hydraulic-mechanical and volumetric losses must be balanced, so that the sum of these losses is minimised. Since the hydraulic-mechanical losses in sealing gaps are proportional to the fluid viscosity, and volumetric losses inversely proportional to viscosity, it is clear that an optimal viscosity must be selected.

Figure 3 shows, as an example, the effect of viscosity on the hydraulic pump efficiency. Apart from the above-mentioned risks in the operation of the device, both too low and too high viscosity are reflected in the efficiency, both volumetric, hydraulic-mechanical, and, consequently, the overall efficiency.

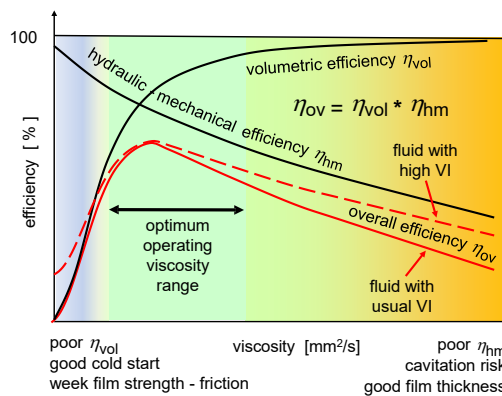


Figure 3: Effects of viscosity on efficiencies [2].

The resulting requirements must be fulfilled by the lubricant, in general: The ability of a lubricant to maintain optimum viscosity under a wide operating temperature range can be achieved with a shear stable, low viscous fluid, with temperature independent viscosity (with high viscosity index VI – see Figure 3), and with a low friction coefficient at both the start and operating temperatures [2].

Higher viscosity index values result in more favourable viscosity behaviour than temperature - favourable Viscosity-Temperature (VI) behaviour, which means less change in viscosity with temperature. From the point of view of the pump, which is the first to start work at the start of the hydraulic system and is the most and permanently loaded during operation, the high value of the viscosity index means fewer problems, both during start-up and during continuous operation. This is especially important when it comes to stricter operating conditions, such as low temperatures on the one hand and higher operating temperatures on the other.

Due to all the aforementioned advantages of low-viscous hydraulic fluids, the direction of development of hydraulic fluids in recent years has been in the direction of fluids with lower viscosity and higher (high) viscosity index. In this way we can reduce drag in the lines, improve cold start-up performance, and improve frictional properties to reduce sliding resistance and increase machine efficiency. In a hydraulic system, pressure loss in the lines is linked closely to the kinematic viscosity of the hydraulic fluid.

In connection with the use of a lower viscosity fluid, however, another issue arises that has not yet received much attention. The lower viscosity of the hydraulic fluid certainly also affects the flow conditions inside the hydraulic tank. This also results in the effectiveness of air bubbles and solid contaminants' elimination.

3 Influence of viscosity on flow conditions in a hydraulic tank

Kinematic viscosity is the most important physical property of lubricating and hydraulic fluids – and it is a criterion for resistance to flowing of the liquid under active pressure. According to the definition, its value is given by the ratio between the active shear stress and shear velocity gradient. Fluid (kinematic) viscosity is

defined by viscosity grade VG (with a deviation of the standard value of +/- 10 %) given at a standard temperature of 40 °C.

The most commonly used ISO viscosity grades in the case of hydraulic mineral oils are VG 15, VG 22, VG 32, VG 46 and VG 68. There are two other ISO viscosity grades, ISO VG 10 and VG 100, but they are rarely used in the field of Hydraulics, more in special cases. In principle, higher viscous fluid is used for higher loads, and lower viscous fluids in cases of lower ambient temperatures (cold start of the device), and in terms of using the fluid as an energy-efficient fluid. Grades VG 22 and VG 32 belong to the low-viscosity oils that are used today as energy-saving fluids.

For the purpose of the simulation studies of the flow conditions inside the hydraulic tank, it is first necessary to obtain accurate material data on the fluids used, in our case, the actual values of viscosity, and also the density of the predicted mineral oil, so we could later compare the simulation results with the experiment. The actual value of the viscosity (and viscosity index) of a specific product can be determined by measuring the viscosity (and calculating the viscosity index). Hydraulic mineral oils of the Hydrolubric VG type (manufactured by OLMA) were used to determine the value of the viscosity of mineral hydraulic oils (and the corresponding viscosity index). For the measurement, we used the standard oil viscosity grade according to ISO, where the oil was VG 46 in two different batches. The exact values of viscosity, as well as the density of the mineral oils used, measured in the manufacturer's laboratory, are given in Table 1. For measuring the kinematic viscosity, in our case, a Cannon-Fenske viscometer with the necessary peripheral equipment (tempered bath, stopwatch) was used, and the measurement performed according the ASTM D445 Standard.

Table 1: Measured values of viscosity and density of the discussed hydraulic oils

Viscosity Grade ISO	Kinematic Viscosity at 40 °C [mm ² /s]	Viscosity Index [-]	Density at 20 °C [kg/m ³]
VG 22 / B1	21.18	107	856.80
VG 32 / B1	34.91	114	862.30
VG 46 / B1	46.98	104	876.20
VG 46 / B2	47.07	119	879.40
VG 68 / B1	70.07	98	881.00
VG 100 / B1	94.01	96	888.30

Remark: B1 – Batch 1, B2 – Batch 2

As a hydraulic tank we used a 30-litre cast aluminium tank for simulation studies – Figure 4. The tank is suitable for a net fluid volume of approx. 27 litres and for normal pump flows of approx. 6 l/min.

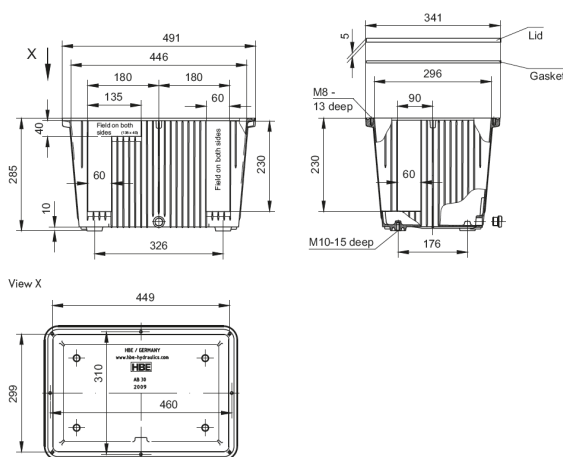


Figure 4: Considered 30-litre aluminium oil tank.

4 Modelling, Mesh, Boundary conditions

A Eulerian approach to describe fluid flow was used in this study. This approach is implemented and readily available in commercial CFD solvers, in this study ANSYS CFX 2020 R2. [6], [7], [8] In all simulations the flow was isothermal, with the fluid properties listed in Table 1, and steady-state mode was selected. The

same operating regime with flowrate $Q_P = 6 \text{ l/min}$ was applied to the numerical simulation of the fluid. In Table 2 the Reynolds number (eq. 1) values in the hydraulic tank inlet and exit pipe are calculated, depending on the flow rate, and used fluid kinematic viscosity.

$$Re = \frac{u d}{\nu} \quad (1)$$

Where u is the fluid velocity in the pipe, d is the pipe diameter and ν is the fluid kinematic viscosity.

Table 2: Fluid properties and Reynolds number value in the hydraulic tank pipes

Liquid (Oil)	Kinematic Viscosity [m ² /s]	Reynolds number value in the inlet pipe	Reynolds number value in the exit pipe
ISO VG 22	0.00002118	275.5	216.5
ISO VG 46	0.00004698	124.2	97.6
ISO VG 68	0.00007007	83.3	65.4

It is evident from the Table that the Reynolds number value in both pipes for all analysed fluid viscosities is in a laminar flow regime. According to this, the fluid flow is described with the continuity equation:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \quad (2)$$

and Navier-Stokes equations:

$$\frac{\partial(\rho \vec{u})}{\partial t} + \rho(\vec{u} \cdot \vec{\nabla})\vec{u} = -\vec{\nabla} p + \mu \nabla^2 \vec{u} + \rho \vec{g} \quad (3)$$

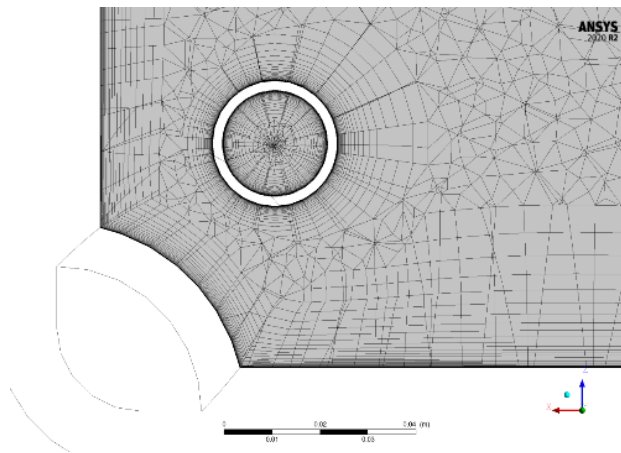
where ρ is fluid density, \vec{u} is fluid velocity, p is pressure, μ is fluid dynamic viscosity and \vec{g} is gravitational acceleration.

Following the laminar flow regime in the hydraulic tank pipes, the higher density mesh was applied for simulation. Details about the used mesh are presented in Table 4.

Table 3: Mesh metrics

Number of elements	Minimum element orthogonality	Maximum element aspect ratio
2,675,435	0.0499	6708

Mesh density near the hydraulic tank wall is depicted in Figure 5.

**Figure 5: Numerical mesh.**

5 Results

The comparison of numerical simulation results for hydraulic mineral based oils ISO VG 22, ISO VG 46 and ISO VG 68 is presented in Figures 6 to 8.

Figure 6 shows streamlines starting at the inlet pipe for all the analysed fluids. It is evident from a comparison of the results that increased viscosity results in a fluid regime that is calmer and more focused. From an integral point of view, we should expect more intensive mixing of fluid and, therefore, fast flow dynamics, with intensive flow to lubricated areas in the case of low viscosity fluid (ISO VG 22).

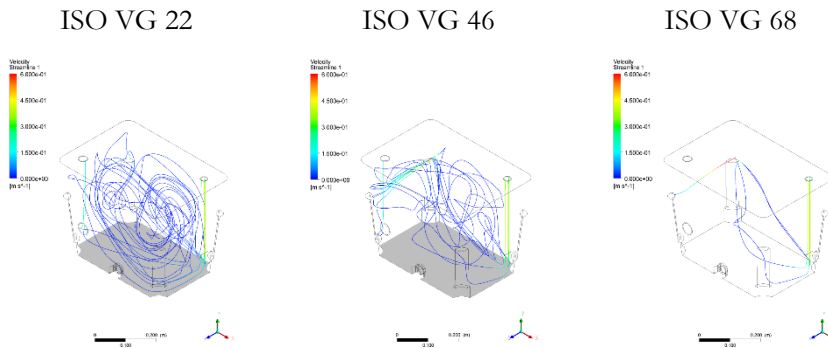


Figure 6: Streamlines in the hydraulic tank for three different viscous hydraulic oils.

Figure 7 shows a comparison of the velocity vector fields in the plane through the centre of the inlet and outlet pipes of the analysed hydraulic tank. Despite the two-dimensional presentation of velocity fields, it is evident that lower fluid viscosity results in smaller local flow structures (vortices), while higher viscosity points out the higher velocity gradients, which may cause lower hydraulic efficiency of the system.

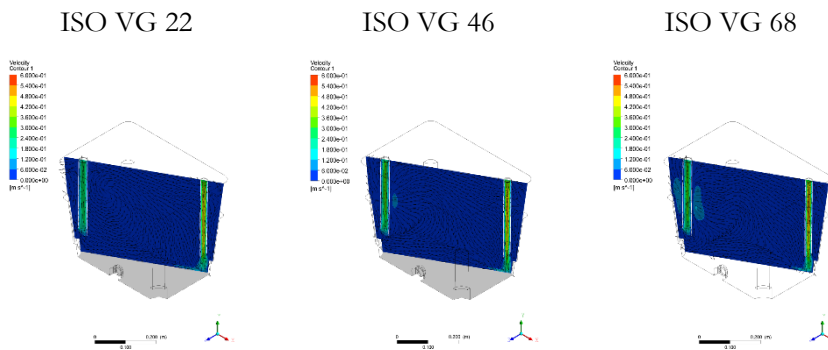


Figure 7: Velocity field in the plane for three different viscous hydraulic oils.

Figure 8 shows the comparison between the shear strain rate at the bottom of the analysed hydraulic tank for all the used fluids. A larger area of increased shear strain rate is evident, which may indicate an intensified fluid regime with poorer excretion of gas bubbles and poorer sedimentation of solid particles in the case of lower viscosity fluids. Higher shear strain gradients indicate more intensive energy dissipation in the case of ISO VG 68.

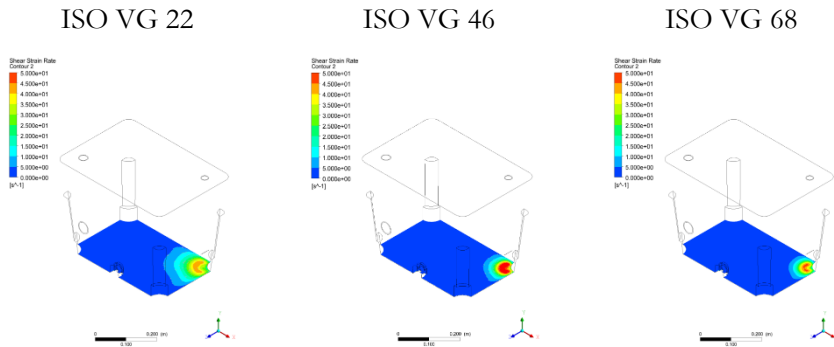


Figure 8: Shear strain rate at the tank bottom for three different viscous hydraulic oils.

6 Conclusion

The trend of development and use of hydraulic fluids goes in the direction of lower viscosity hydraulic fluids, but with higher values of the viscosity index. The main reason for this is to improve the efficiency of the hydraulic system. However, the lower viscosity of the fluid, in addition to what happens inside the active hydraulic components such as pumps and valves, also affects the flow conditions inside the hydraulic tank.

Due to the lower viscosity of the fluid, the flow inside the tank is expected to be livelier, which also affects the settling and distribution of solid contaminants, the excretion of air bubbles and the cooling of the liquid through the tank walls. This needs to be examined further and considered if lower viscosity hydraulic fluids are used.

References

- [1] Javalagi, S., Singireddy, S. (2012) Hydraulic fluid properties and its influence on system performance. Master's Thesis, LIU-IEI-TEK-A--12/01284—SE, Linköping University, Sweden
- [2] Lovrec, D., Tič, V. (2020). Ionic liquids as wide operating temperature range lubricant. *New technologies, development and application III : [International Conference New Technologies, Development and Application, Sarajevo, Bosnia and Herzegovina, on 25-27 June 2020]*, ISSN 2367-3370, Vol. 128). Cham: Springer. cop. 2020, vol. 128, pp. 348-359, doi: 10.1007/978-3-030-46817-0_40
- [3] Eneos (2016). Energy-Saving Hydraulic Fluids, <https://www.eneos.co.jp/english/company/rd/intro/lubricants/shoene.html> (6. 8. 2021)

- [4] Rydberg, K. E. (2013) Hydraulic Fluid Properties and their Impact on Energy Efficiency, *13th Scandinavian International Conference on Fluid Power Proceedings*, Linköping, Sweden, ISBN: 978-91-7519-572-8; Article No. 44, 447-453
- [5] Rydberg, K. E. (2015). Energy Efficient Hydraulics – System solutions for loss minimization, *National Conference on Fluid Power*, Linköping University, Linköping, Sweden.
- [6] Škerget, L. (1994). Mehanika tekočin. Tehniška fakulteta v Mariboru, Univerza v Mariboru in Fakulteta za strojništvo v Ljubljani, Univerza v Ljubljani
- [7] Ansys, INC. (2021). ANSYS CFX Solver-Theory Guide, Release 2021 R1. ANSYS, Inc., 275 Technology Drive Canonsburg, PA 15317
- [8] Rodriguez, S. (2019). Applied Computational Fluid Dynamics and Turbulence Modelling, Practical Tools, Tips and Techniques, *Springer Nature Switzerland AG*

