SLM 3D printed proportional directional water hydraulic valve, tested with optimized mounting plate

Jan Bartolj[1], Ana Trajkovski[1], Marko Hočevar[1], Katharina Schmitz[2] and Franc Majdič[1]*

1. Laboratory for fluid power and controls, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva ulica 6, 1000 Ljubljana, Slovenija
2. Institute for Fluid Power Drives and Systems (IFAS), RWTH Aachen University, 52074 Aachen, Germany

E-mail: jan.bartolj@fs.uni-lj.si

Abstract

In this study, we investigate the influence of pressure transducer installation and mounting plate geometry on the accuracy of flow characterisation in a 3D printed proportional directional control valve system. The valve itself, which was developed in our previous research work, has been confirmed numerically and experimentally. To allow measurements to be as accurate as possible, we designed and manufactured highly optimised mounting plate with integrated pressure transducers using SLM additive manufacturing process.

The main objective was to assess whether the position of pressure transducer and the internal geometry of the mounting plate affect the accuracy of the measurement and cause interference that could affect the determination of the flow characteristics of the valve. Conventional and 3D printed mounting plate configurations were tested under controlled conditions, including versions with external and integrated pressure transducers. Experiments were carried out using two fluids: ISO VG 46 mineral hydraulic oil and standard tap water, which allowed us to estimate performance under flow conditions with high and low viscosity.

The results of our measurements have shown that 3D printed mounting plate with integrated pressure transducers provided the lowest pressure drop in the system and allowed the most accurate characterization of the valve performance. Specifically, the integrated transducer configuration reduced pressure drop by 47 % compared to settings with external transducers. Reduction of pressure drop significantly reduced the effect that disturbing factors have on measurement, resulting in more reliable results. In addition we determined that location where transducer is integrated has great influence and it becomes increasingly important at higher flow rates, where differences in measurement location resulted in more significant deviations. The study highlights the benefits of additive manufacturing in creating application-specific hydraulic components that improve transducer integration and by that measurement accuracy.

Keywords: water hydraulics, valve, mounting plate, optimisation, additive manufacturing

1 Introduction

Recently, it has become clear that systems, machines and parts should be as efficient as possible in order to conserve material and energy resources. This is being repeated constantly in recent years, but fulfils a lot of global climate and continual development goals. Especially in the field of hydraulics, the use of new manufacturing technologies has proven to be extremely useful and in direct correlation with the development of components. Additive manufacturing (AM) allows users to make a variety of improvements based on more or less extensive numerical optimization [1].

2 Theoretical background

Nowadays, it should no longer be a question of whether to use optimisation software or not, but which one to use and to what extent. As AM is a way of manufacturing that imposes few to no constraints on designers, many extremely optimised components and systems have already been introduced in the field of hydraulics [2-4] and beyond.

2.1 Additive manufacturing

When we talk about AM in hydraulics, we emphasize 5 main advantages. AM allows us to:

1. Create complex geometries:
    - Internal and external geometry optimisation,
    - Customization.
2. Create lightweight, optimised designs:
    - Reduce the volume of parts compared to conventional manufacturing (CM), so that less material is used and the same functionality is achieved while less energy is consumed in manufacturing [5], all in the light of global climate policies.
3. Rapidly produce prototypes:
    - The production of prototypes and small series could be carried out quickly and cost-effectively.
4. Efficiently use base materials:
    - Since AM uses only the material that is critical to the structural integrity of the component, AM is much more efficient compared to CM. In addition, material that was not used in one process can be used in the next process.
5. Consolidate multiple parts into a single structure:
    - One of the strongest, but most overlooked points is definitely the consolidation of components. This allows designers to merge multiple components into a single body unit that has the same functionality, but in most cases is significantly more efficient.

All in all, AM is transforming the way that hydraulic components are designed and produced by enabling more efficient use of materials and enhancing performance. Main disadvantage could be found in the relatively high cost of machines for AM and so the process itself, but with the development and introduction of new and more optimised machines, combined with improved performance of components, even slightly higher cost of manufacturing should be justified [6].

2.2 Water hydraulics

Water hydraulics is a sub-discipline of hydraulics in which mineral hydraulic oil or other types of hydraulic fluids are replaced by pure tap water. Water has a higher density than the commonly used hydraulic fluids, but a lower viscosity. The use of water as a hydraulic fluid has many advantages and some disadvantages. The main advantage is environmental friendliness, because in the event of a leakage or replacement of the working fluid, the water can simply be disposed of as it has no negative impact on nature. The main advantages are therefore: environmental friendliness, availability and fire resistance. On the other hand, water poses some challenges that need to be overcome in order for users to replace mineral or synthetic oils with water, such as the use of suitable non-corrosive materials that have at least some self-lubricating properties. Since water also has a lower viscosity than oil, it is more susceptible to cavitation. The disadvantages drive up costs, so most industries still use mineral hydraulic oils, but there are exceptions where cleanliness or fire safety are of the most importance. It has already been shown in some studies that there are a number of materials that are compatible with water hydraulics and can also be interchanged between oil and water hydraulics [7]. In this study, authors have tried to compare the results of the same component used in oil and water hydraulics to ensure that it can be easily interchanged and used in both.

2.3 Pressure loss as an identificator of performance

The pressure drop could be determined mathematically with the help of equations. However, this approach only provides us with an approximation or a range in which we can expect the result of the measurement.

To determine the pressure drop as a function of the flow of the hydraulic fluid, the density and the cross-sectional area of the flow, we need to use the basic Bernoulli equation (1). In the Bernoulli equation, we have pressure, velocity and potential component, all of which must remain in correlation, regardless of how the geometry changes. This ensures basic continuity.

$$p + \frac{1}{2}\rho v^2 + \rho g h = const. \tag{1}$$

Derived from the Bernoulli equation of energy conservation (1) and using a shape coefficient of the orifice respectively, we get the equation from which we can determine the flow rate as a function of the pressure drop for a known orifice cross-sectional flow area (2).

$$q_v = C_d \cdot A_{orif} \sqrt{\frac{2 * \Delta p}{\rho}} \tag{2}$$

Also surface roughness of internal structure of 3D printed components is usually considered, but since our experience have shown that most of hydraulic pressure drop is due to local and not linear losses, we have neglected it in this study.

3 Experimental work

In 2022, 2 iterations of 3D printed highly optimised valve body geometries were developed in our Laboratory of fluid power and controls (*Slo: Laboratorij za fluidno tehniko, LFT*) [8,9]. The main focus of the recent work was on the design and CFD tests, while real tests were not performed on a large scale. In this paper, we will present the tests we conducted with an AM produced valve body and compare the different effects of using mineral hydraulic oil and pure tap water. We have also designed and 3D printed a hydraulic mounting plate with integrated pressure transducers to measure the pressure difference between the inlet and outlet channels of the valve. Until this new and improved base plate, we were not able to measure the pure pressure difference of the valve, but the measurement was affected by many couplings, hoses, T-junctions and the base plate itself, which were located between the transducer and the measured valve. This adds a lot of uncertainty to the measurement, which we tried to eliminate by placing the transducer as close as possible to the valve body. This meant that the measuring point had to be integrated

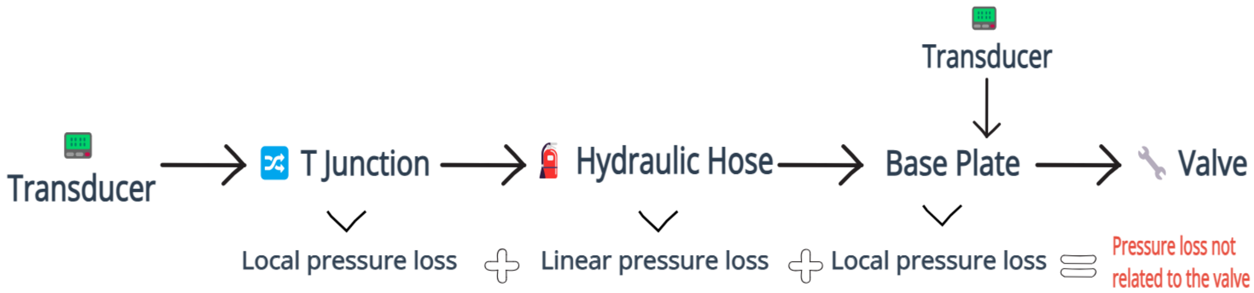

Figure 1: Measurement chain

into the base plate, close to the valve itself. We also tried to design the base plate to be as easy to handle as possible without the hydraulic couplings being too close to make screwing easier. The diagram in figure (1) shows the way we have installed the pressure sensors in the inlet branch of the valve. A pressure transducer is mounted at the beginning and has 3 elements (T-junction, hydraulic hose and base plate) that add to the pressure drop before measuring the pressure drop of the actual valve. We have therefore integrated pressure transducers directly under the valve itself (as shown by the second transducer connected directly to the base plate). We expect a slightly lower pressure drop compared to the measurement with the conventionally placed pressure transducer. Additional hydraulic losses are indicated below the measuring line of the pressure transducer on the far left which contribute to the measurement uncertainty and are avoided if a transducer is used below the valve body.

Testing was carried out at two testing facilities. Oil test facility has 20 kW of hydraulic power and was limited to 350 bar of pressure. For water hydraulic tests we used self-developed testing facility that has 11 kW of hydraulic power. Again, highest pressure with water hydraulic tests was limited to 350 bar that gave us approximately 30 l/min flow rate.

3.1 Valve and plate assembly

Figures 2 and 3 show the comparison between the conventionally manufactured (CM) and the 3D-printed base plate. The CM base plate is bulkier, and since all the connections for hydraulic fittings are from the underside, it is quite difficult to mount the pipes to close the hydraulic circuit. And since the pipes are mounted from below, the base plate cannot stand alone but must be attached to some kind of bracket. The base plate produced using additive manufacturing (AM) (Figure 3) is optimised for easier assembly and is much easier to handle as each connection points in its own direction. It can be operated as a stand-alone element, even when installed in a hydraulic circuit. The main advantage of the AM base plate is the possibility of integrating transducers close to the directional control valve that is mounted on it.

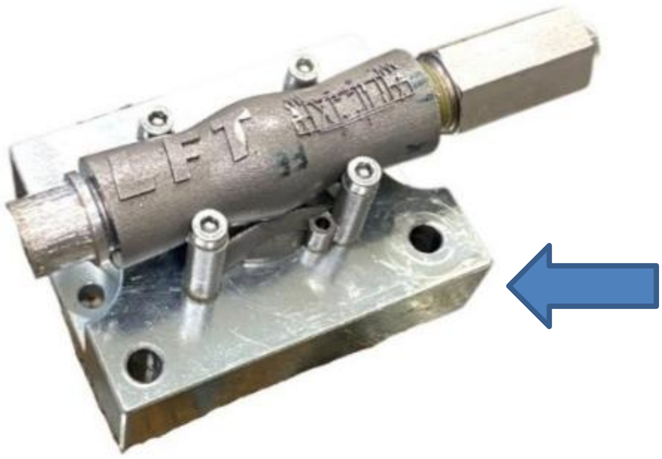

Figure 2: Conventionally manufactured (CM) base plate with spool valve attached.

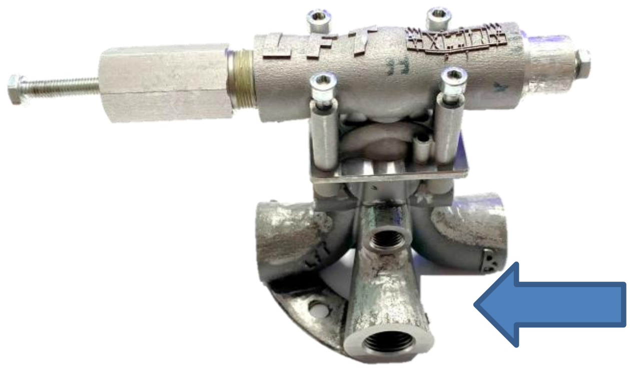

Figure 3: Additively manufactured (AM) base plate with spool valve attached.

As already mentioned, we used a hydraulic valve body that was optimised and 3D-printed in 2021 [8]. We used a spool that has 3 control notches with a notch width of 2 mm. To position the spool in the valve, we used two screws, one from each side, to ensure that the spool is not displaced by the flow forces. The structure and assembly of the valve is shown in the Figure 5 and consists of the following elements: 1. valve body, 2. core of the positioning screw, 3. positioning screw, 4. controlling spool, 5. washer that pushes the slider into the centre position, 6. stainless steel spring, 7. two 1 mm washers to ensure spring preload, 8. sealing washer, 9. core of the

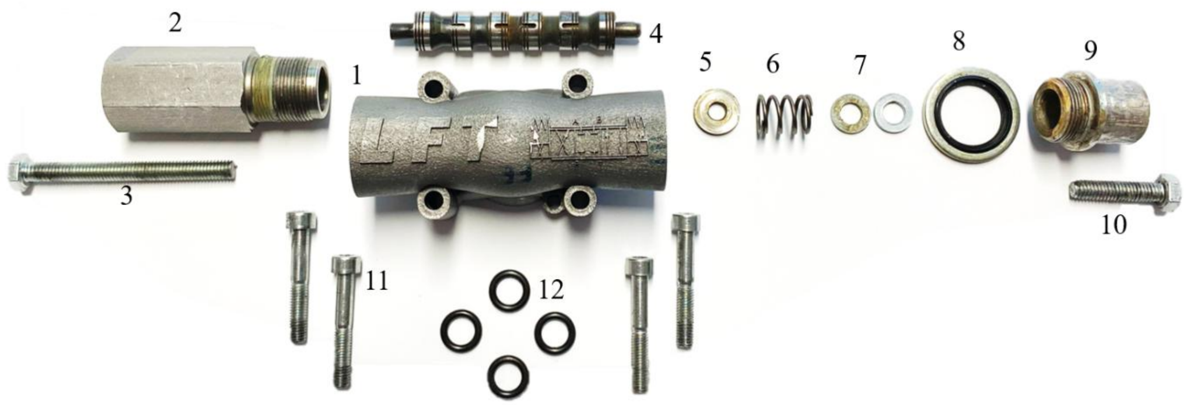

Figure 5: Directional spool valve assembly.

counterpositioning screw, 10. counter-positioning screw, 11. fixing screws, 12. static O-ring seals.

Figure 4 shows where the pressure transducers were installed in the mounting plate. The lower holes with the corresponding letters on the side, indicating the individual channels P, A, B and T, were used to connect the hydraulic G 1/2 fittings, and the upper holes were used to insert the standard Minimess fittings that connect the mounting plate to the pressure transducer. The transducers and all the measuring equipment were manufactured by Parker. We used Parker Service Master Plus (K-SCM series) to collect the data from the transducers and export the measurements.

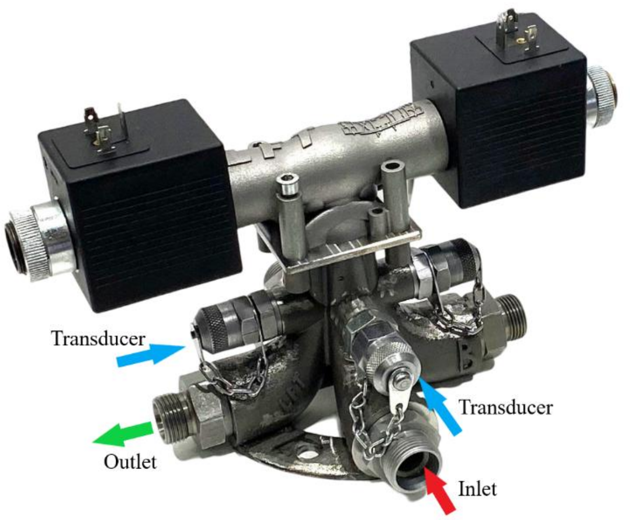

Figure 4: Installation of pressure transducers integrated into additively manufactured mounting plate.

Figure 6 shows the actual measurement setup with all connectors and measuring transducers fitted. The picture also shows the flow direction and the way in which the 4-point measurement of the mounting plate manufactured by AM was carried out.

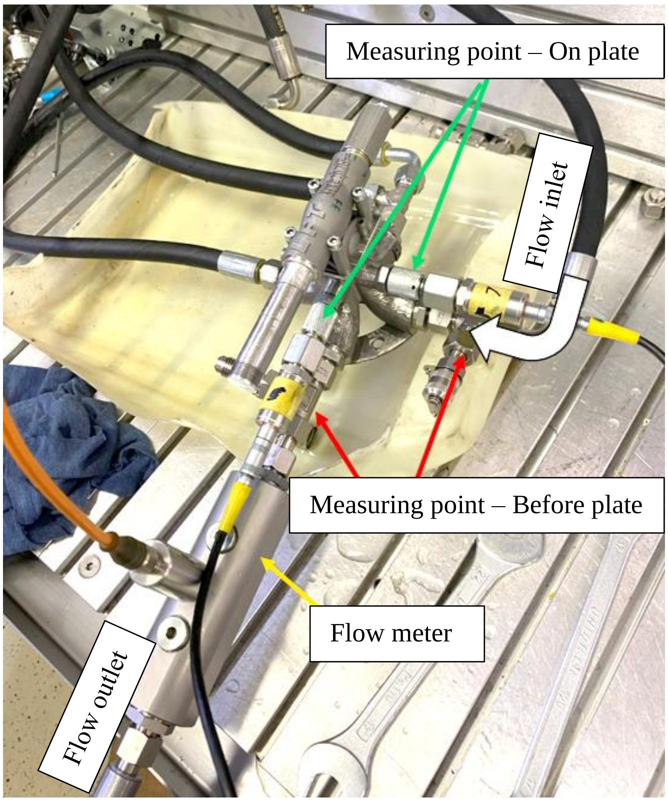

Figure 6: Valve assembly on the water testing rig, with pressure transducers and flow meter attached.

4 Results

During the measurement, we realized that the valve felt quite hot. We therefore used a thermal imaging camera (FLIR E6 Pro) to determine how much the valve and the AM plate were heated by the flow of ISO VG46 (Figure 7). The highest temperature measured during the tests was around 65°C at the valve body. The oil in the reservoir had a secondary cooling circuit that was set to maintain the temperature of the reservoir at 40 °C, which was in perfect condition. The fluid flow heats up valve body due to the narrow paths and pressure drop since this is the main heat sink for approximately 22 kW of hydraulic power. We can assume that the spool inside the valve body heats up even more, as the notches are the places where the flow is most restricted due to the small cross-sectional area.

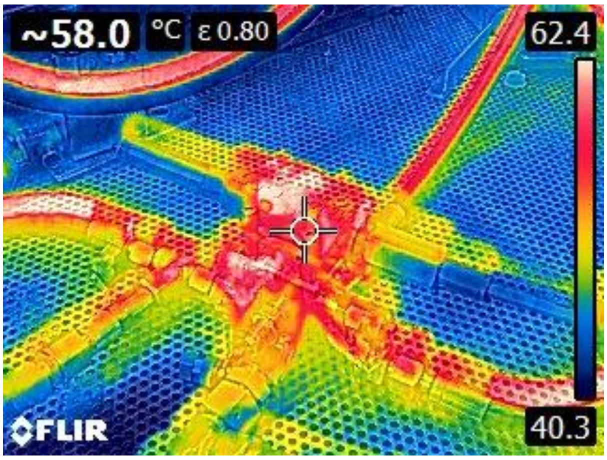

Figure 7: Image from thermal imaging camera, showing heat buildup in the valve and AM base plate assembly during ISO VG46 mineral hydraulic oil testing.

4.1 ISO VG46 measurement

Firstly, we present the measurement carried out with ISO VG46 mineral hydraulic oil using the CM and AM mounting plate. Simple calculation using equation 2, gives us estimated pressure drop of 67,8 bar at the control notches of the spool at 50 % opening and 30 l/min flow rate. AM mounting plate had 4 sensors measuring simultaneously, two on plate and two before plate, as it can be seen in the Figure 6. The pressure drop depends strongly on the position of the spool in the valve body and the flow rate of the liquid. The further away the spool is from the center position, the larger the cross-sectional area of the fluid flow and the lower the pressure drop through the spool control notches and the valve itself. Conversely, the higher the flow rate at constant spool displacement, the higher the pressure drop. In all cases with a higher flow rate (30 l/min), we measured a higher pressure drop (Figure 8) than with a lower flow rate (20 l/min). In all cases, the CM mounting plate performed the worst when comparing the same spool displacement. When comparing the measurement of the pressure drop before and on plate, we can see the similarity, as the difference is only about 1 to 2 bar pressure drop. At a flow rate of 30 l/min, we measured a constant or slightly increased pressure drop after 60 % opening. This was due to the effect of pressure compensator on the variable displacement pump. It tries to increase the flow rate and consequently increases measured pressure drop at the valve, but in the case of this measurement it was the disturbing factor. In future we should use a constant displacement pump.

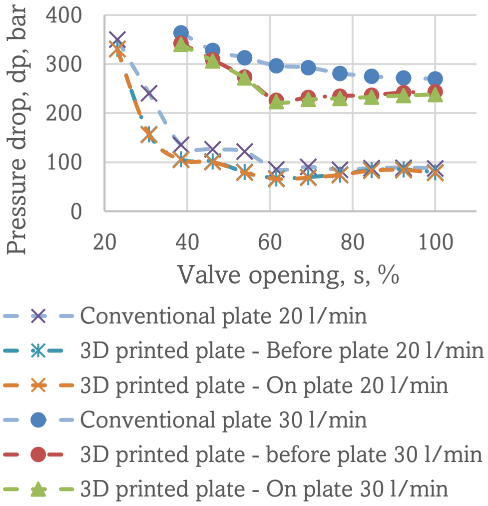

Figure 8: ISO VG46 mineral hydraulic oil measurement of pressure drop at 20 and 30 l/min at variable valve opening.

In the Figure 9, we have shown the pressure drop at two different opening states of the valve at 30 % and 60 %. Logically, a larger valve opening also reduces the pressure drop since flow area is larger. This figure also shows that the pressure drop at constant valve opening increases with increasing volume flow. A clear difference between the CM and AM mounting plate can also be seen here. The AM mounting plate significantly reduces the pressure drop, but the difference between the measurement before and on the plate is quite small.

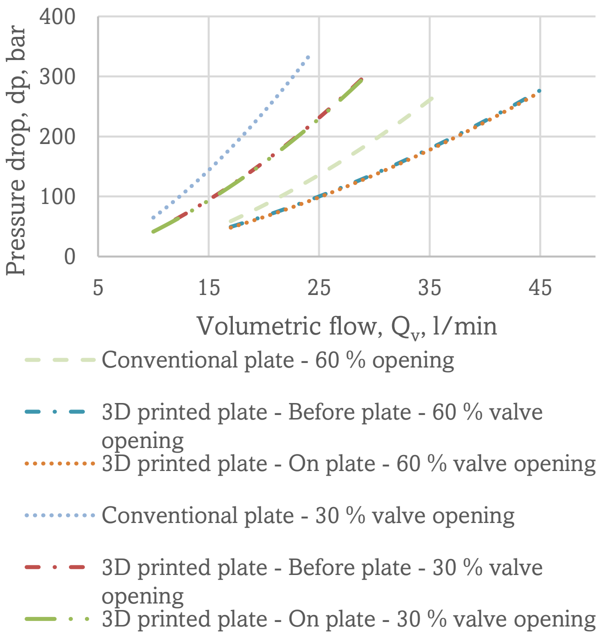

Figure 9: ISO VG46 mineral hydraulic oil measurement of pressure drop at 30 % and 60 % valve opening at variable flow rate.

To compare the differences between the measurement before and on the plate, we have plotted the deduction of the pressure drop before plate and on plate (Figure 10). We can see that the difference between the two values increases almost linearly for both a 30 % and a 60 % opening of the valve. This means that the real added value of the optimised AM mounting plate becomes significant at the higher volumetric flows, which also leads to a more accurate measurement of the valve itself. However, when comparing the opening at the same flow rate, it can be seen that the difference between pressure drops upstream and downstream of the plate is quite similar, differing by only 8 % on average.

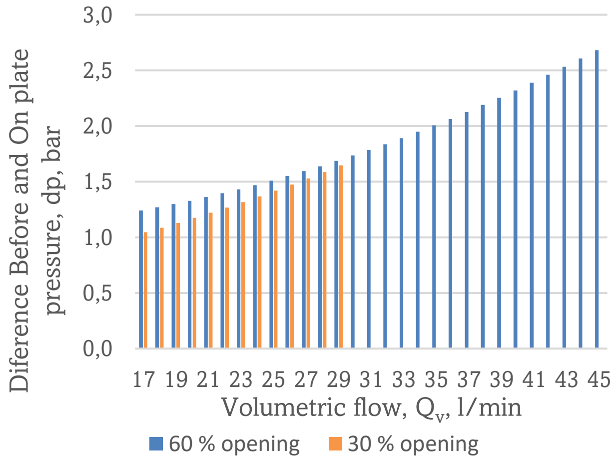

Figure 10: ISO VG46 mineral hydraulic oil. Calculated difference between measurements obtained during simultaneous 4-point measurements on AM mounting plate at 30 and 60 % valve opening and variable volumetric flow.

4.2 Tap water measurement

In the second part, we repeated the measurement, but using tap water as the flow medium and a specially adapted 11 kW water test system. The maximum capacity of this system is 30 l/min at pressure 350 bar. It would therefore not be possible to achieve the same properties as in the first tests with an oil system that has a capacity of 20 kW. Nevertheless, we expected a certain degree of comparability with the same flow rates that were achieved. Using equation 2, again gives us estimated pressure drop at the control notches of the spool. Using water properties at 50 °C and flow rate of 20 l/min gives us the 34,7 bar of pressure loss at 50 % opening. As our CM mounting plate was not intended for use with water, we were unable to measure the properties of both plates in water, but we did manage to do so with the AM plate.

The results show that the shape of the characteristic curve (Figure 11) is similar to the one we obtained when measuring with oil. The pressure drop is lower at the same flow rate when we open the valve and thus increase the flow area through the control notches. The measurements were carried out at a flow rate of 5 l/min and 20 l/min, with the data recorded both before and on plate at the same time.

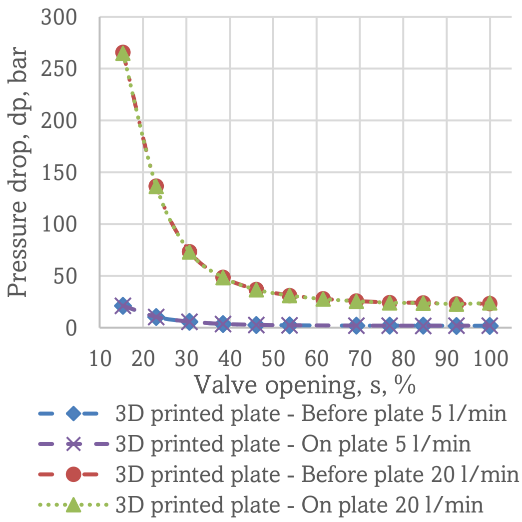

Figure 11: Tap water measurement of pressure drop at 5 l/min and 20 l/min at variable valve opening.

As with the first measurements, we set a valve opening of 30 % and 60 % and measured the pressure drop with increasing volumetric flow. Again, we measured an almost perfect second order curve of the pressure drop through the valve (Figure 12).

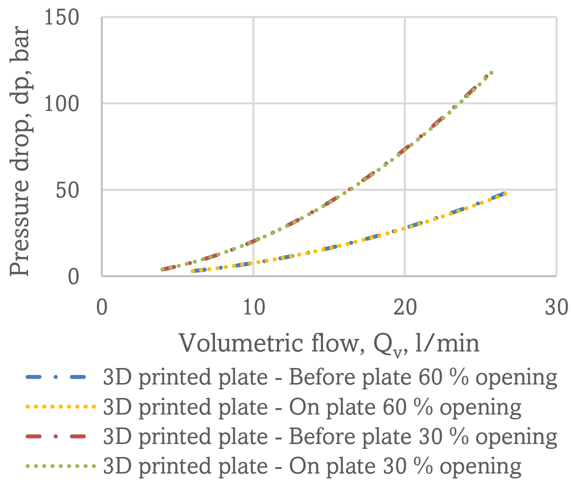

Figure 12: Tap water measurement of pressure drop at 30 % and 60 % valve opening at variable volumetric flow.

The difference between the measurements before and on the plate is shown in Figure 13. Here too, we can see that the difference increases at higher flow rates, similar to the oil measurement. It therefore makes sense to use this plate for more accurate measurements at higher flow rates.

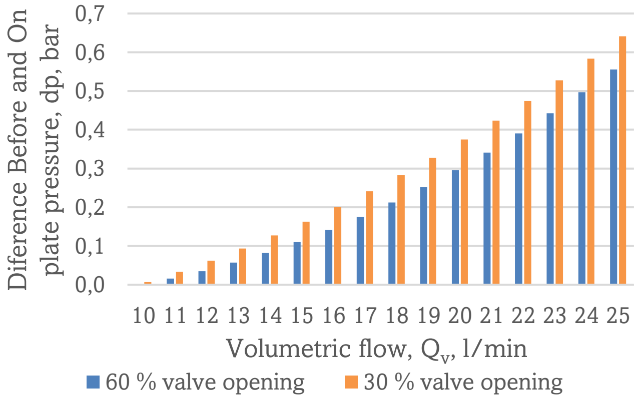

Figure 13: Tap water calculated difference between measurements obtained during simultaneous 4-point measurements on AM mounting plate at 30 % and 60 % valve opening and variable flow rates.

5 Comparing results of ISO VG46 and water

In this chapter we will discuss the differences between oil and water measurements. In Figure 14 we have shown the pressure drop for different flow rates at a constant valve opening of 30 %. It can be clearly seen that water has a lower pressure drop, which is directly related to the lower viscosity. Figure 15 shows a similar trend when comparing oil and water, but at a valve opening of 60 %, and the difference is almost identical. In all cases, it is again evident that the CM plate performs worst in absolute terms, while the 4-point simultaneous measurements of the AM plate always show very similar properties, which is to be expected.

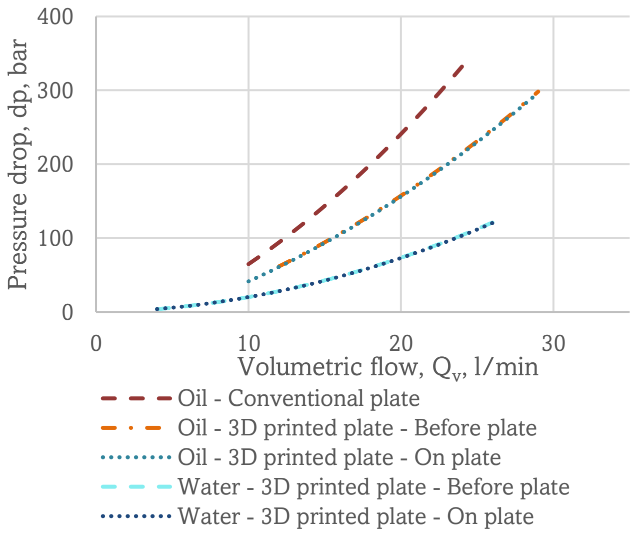

Figure 14: Comparison between water and ISO VG46 mineral hydraulic oil and CM to AM mounting plate measured characteristics at constant 30 % valve opening and variable flow rates.

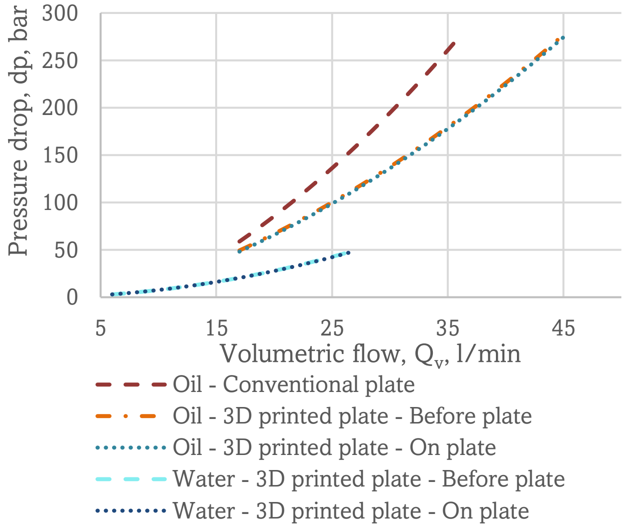

Figure 15: Comparison between water and ISO VG46 mineral hydraulic oil and CM to AM mounting plate measured characteristics at constant 60 % valve opening and variable flow rates.

6 Conclusions

From the results we can conclude that it simply makes sense to use an AM mounting plate over a CM plate. As already mentioned, there are many advantages, from easier mounting to better performance and more accurate measurement. The AM plate is only partly held back by the cost, but as this work clearly shows the level of measurement accuracy achieved with the CM plate, the use of the AM plate with integrated sensors makes more sense, especially at higher flow rates.

Future work

The next steps in this study would be to optimise the shape of the internal geometries to further improve the performance of the AM valves. We believe that the development of self-supporting structures and their flow characteristics would lead to a next generation of high-performance hydraulic components developed using AM. Another step forward, could also be, to make AM mounting plate even more user-friendly and more optimised.

Acknowledgements

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Nomenclature

Variables used in equations are presented in the table below.

Designation	Denotation	Unit
A_{orif}	orifice cross-section area	m^2
C_d	orifice contraction coefficient	/
g	gravity	m/s^2

h	hydraulic height	m
p	pressure	Pa
Δp	pressure difference	Pa
q_v	volumetric flow	l/min
v	velocity	m/s
ρ	fluid density	kg/m^3

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