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Flow conditions inside a small hydraulic tank at excessive flow rates

DARKO LOVREC & IGNACIJO BILUŠ

Abstract The basic purpose of a hydraulic tank is to hold a volume of fluid, transfer heat from the system, allow solid contaminants to settle and facilitate the release of air and moisture from the fluid. To perform these important tasks more efficiently, the tank must be dimensioned properly. Above all, it must have an appropriate size. If the tank is too small the flow conditions inside the tank deteriorate, resulting in inadequate conditioning of the hydraulic fluid. Based on the simulation, the paper presents the difference in the change of flow conditions in the case of adequate and insufficient tank sizes. A small industrial hydraulic tank with a capacity of 30 litres filled with hydraulic mineral oil was used as the example of the study.

Keywords: • hydraulic tank • sizing • circulation number • flow condition • simulation •

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

1   Introduction

The primary function of a tank in a hydraulic system is to store the fluid used by the system. Apart from e fluid storage, the tank provides a variety of other functions that are beneficial to the hydraulic system and its components, and most of them are related to the size of the tank.

As fluid flows through hydraulic system it warms up wherever friction is generated by the fluid flow or by moving the mechanical parts inside hydraulic components. As the fluid circulates back to the tank, the heat is dissipated into the surrounding atmosphere, because there are large areas of tank housing from which it can be released. A more powerful cooling system must be installed in the case of a tank that is too small, and, consequently, has too small tank surfaces.

The next important task, which is also related to the size of the hydraulic tank, is the extraction efficiency of air in form of air bubbles. Air can be introduced into hydraulic fluid in variety of ways: During the movement of the cylinder, via leaky pump suction pipe connections, due to improper design of the inside of the tank (e. g. from the return flow jet due to too short a return pipe), or due to large occasional stirring turbulence of the liquid in the tank occurring during a sudden increase in return flow. Whatever is the cause, air bubbles must be removed from the hydraulic fluid as quickly as possible. If sized properly, the tank serves as a place where the fluid can settle down for a period a time to allow the air to rise to the surface and dissipate before being pumped back into the system.

Also, in the elimination of solid particles – solid contaminants, the size of the tank plays an important role. They can enter the hydraulic tank from a contaminated environment, or are generated internally, inside the hydraulic system as a result of component wear. These particles enter the tank through the return flow. Larger particles, especially metallic ones, settle at the bottom, and usually do not get recirculated back into the system by the pump. However, it takes some time for these particles to settle. The higher the efficiency of particle extraction is the calmer is the flow of fluid in the hydraulic tank.

Slowing the fluid flow inside the tank has an effect, and the associated effects on the elimination of air bubbles and solid contaminants are related directly to the tank`s size. In the case of too small a tank volume, the flow conditions inside the tank are unfavourable, and worsen the processes of removing contaminants.

2 Sizing the tank and circulation ratio

Various recommendations can be found in the professional literature, different publications and posts regarding the appropriate tank size, both by tank manufacturers and users of hydraulic systems (e. g. [1], [2], [3], [4]).

So often we come across a recommendation that, in general, for most industrial applications, the minimum reservoir size should be approximately 2.5 or 3 times the pump(s) flow – a so-called rule of thumb. Additionally, consideration must be given to the return flow, which may be greater than the original pump flow.

The rule of thumb "three times the flow rate" should be considered in more detail, given the limitations on the installation space and the economics of using the hydraulic device. The first thing that needs to be determined when sizing a hydraulic tank is the size and oil requirements of all components, such as cylinder displacements, accumulator volumes, etc. Secondly, heat must be a factor, as this results in any unused power being converted to heat. Dissipating this heat can only be effective if a tank is sized with a sufficiently big surface area, which allows a temperature difference to exist between the oil and ambient environment to dissipate the heat.

From this point of view, the following recommendation could be made: "Bigger is better". Due to the larger tank volume the longer t dwell time the fluid must have to give up contaminants – solid particles, water and particularly air. But as there is not always the possibility to find a lot of space for placing the tank, we need to know and follow the minimal requirements for system calculation.

It is necessary to consider the following factors when designing a hydraulic tank:
- – Enough oil must be kept for system function,
- – An adequate surface area to dissipate heat,
- – Sufficient volume to minimise turbulence and allow air bubbles to escape and contaminates to settle,

- Keeping the suction and return lines separated,
- The use of baffle plates between the suction and return lines,
- Access for maintenance and cleaning,
- Room for installing system components.

When dimensioning and designing a tank we can also look at Standards and Recommendations e. g. NFPA/T3.16.2 and ISO 4413: 2010, as two essential documents when designing a new hydraulic power unit. Table 1 summarises all the available information regarding the appropriate tank size.

Table 1: Generally recommended tank size values

Minimum value	Recommendation
Industrial application – mineral oil	
2.5 times all pumps` flow	3 to 5 times all pumps` flow
Industrial application – HFC and HFD	
5 times all pumps` flow	8 times all pumps` flow
Mobile application – Open loop system	
1.5 to 2 times all pumps` flow	2.5 times all pumps` flow
Mobile application – Close loop pumps	
1 to 2 times all charge pumps` flow	1.5 to 2 times all pumps` flow

In the case of the use of HFC or HFD fluids, which generally have a higher density, the elimination of contaminants is less efficient. Therefore, the recommended tank volume is larger. In all cases, however, the obtained tank volume value must be increased by approx. 10 to 15 % (air cushion, fluid level fluctuations due to thermal expansion of the fluid and chambers of different sizes in hydraulic cylinders…).

The ratio between the tank volume V_T and the flow of the pump Q_P can be given in the form of circulation ratio C_r. Similarly, such a ratio may also be used in the case of other tanks, e. g. for bearing lubrication systems, and can be given in different ways, as V_T vs Q_P, or vice versa. [5], [6] As written in Table 1, the circulation ratio can be given as:

$$C_r = \frac{V_T}{Q_P} \qquad [min] \tag{1}$$

The circulation ratio indicates how often the entire fluid volume in the tank is recirculated or pumped per time interval, e. g. per minute. In harsher operating conditions, the fluid (e. g. oil) needs more time to recover (otherwise the entire filling will need to be replaced more frequently). This applies, for example, in the case of higher temperatures and low oil quantities with a low value of circulation ratio. According to the record in Table 1, a higher value of C_r is desired.

In the case of (too) small tanks, both in the fields of stationary and mobile hydraulics, the elimination of contaminants is worse. Depending on the flow of the pump, a too small selected tank volume leads to overheating and faster ageing of the hydraulic fluid, to a shorter service life of the installed hydraulic components due to faster wear and to many other side effects, such as e. g. increased elasticity of drives, greater oscillations and signal delay, diesel effect and cavitation, varnishing and sludge…

3   Small hydraulic tanks and excessive pump flow

The too small selected tank volume in relation to the pump flow is not always the result of an error in sizing and selecting the tank size. In certain cases, however, we want to have smaller tanks according to the flow of the pump. This is especially useful or desirable in the case of testing the durability of hydraulic fluids, e. g. mineral oils, because, in the test, we want to load the fluid more and degrade faster. These are so-called tribological tests with hydraulic pumps. Some typical parameters of such established tribological pump tests are given in Table 2.

Table 2: Circulation ratio values of different tribological pump tests

Test	Tank fluid volume [l]	Volumetric flow rate [l/min]	C_r [min]
Denison Vane Pump HF0 Test	189	265	0.71
Sundstrand Piston Pump – Series 22	45	95	0.47
Vickers test with a 35VQ-25 pump	196	144	1.36
Komatsu test	75	20 to 60	3.75 to 1.25
Integrated durability test device [7]	27	11	2.45

In all these mentioned tribological tests with hydraulic pumps, the values of the circulation ratio are much lower than those recommended for normal operating conditions e. g. when using mineral oil at the recommended tank size as 3 to 5 times the pump flow value (see Table 1).

The flow conditions in the tank are not visible to the naked eye, and are therefore not known exactly, as the tanks have a metal housing. It does not matter whether the too small volume of the tank is due to an error in choosing the appropriate size of the tank, or whether a smaller volume of the tank is chosen purposely than e. g. in the case of tribological tests with pumps.

In our case, the flow conditions in the undersized hydraulic tank were studied based on an industrial 30-litre aluminium cast tank used in the case of the integrated test device mentioned in Table 2. There was 25 l of mineral oil in the tank. The appearance of the considered tank is shown in Figure 1.

Figure 1: 30-litre cast aluminium oil tank.

4   Simulation of flow conditions inside a small tank

Insight into the flow conditions inside the tank and the influence of different designs and dimensions of the tank is provided by a computer simulation based on the appropriate numerical model of the hydraulic tank and the relevant parameters of the tank. The latter can be obtained based on comparative experimental research, or based on the experience of previous research. Simulation of flow conditions and phenomena inside a hydraulic tank have been the subject of several studies [8], [9], [10], [11], [12], [13].

A Eulerian approach to describe fluid flow is used in this study. This approach is implemented and readily available in commercial CFD solvers, and the ANSYS CFX 2020 R2 was used in this study. In all simulations the flow was isothermal, with the fluid properties for ISO VG 46 listed in Table 3 and steady-state mode selected. Three different flow rates were prescribed to simulate normal, increased and excessive flow rate in the system. Both inlet and outlet boundary conditions were prescribed as average inlet and outlet velocity, and all other surfaces of the tank were taken as no-slip walls, as shown in Figure 2.

Table 3: ISO VG 46 mineral oil properties used in the simulations

Viscosity Grade ISO	Kinematic Viscosity at 40 °C [mm²/s]	Viscosity Index [−]	Density at 20 °C [kg/m³]
VG 46	46.98	104	876.20

The reference pressure within the computational domain was set to 1 atm, an advection numeric scheme was chosen to be upwind, and Root Mean Square (RMS) convergence criterion was set to 10^{-4} for all equations.
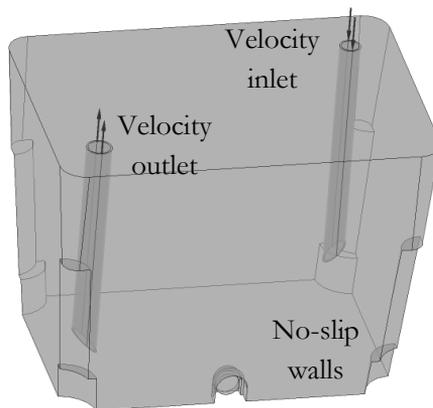
Figure 2: Boundary conditions.

In Table 4 the test cases are presented with the circulation ratio (eq. 1) and Reynolds number values (eq. 2). The Reynolds number is calculated as:

$$Re = \frac{u\,d}{v} \tag{2}$$

where u is the fluid velocity in the exit pipe, d is the pipe diameter and v is the fluid kinematic viscosity.

It is evident from the Table 4, that Reynolds number value in exit pipes for all analyzed fluid flowrates is in laminar flow regime.

Table 4: Test cases and boundary conditions used in the simulations

Test case	Volume of fluid in the tank [l]	Volumetric flow rate [l/min]	Cr [min]	Reynolds number value in the exit pipe
Recommended flow rate	27	6	4.5	275.5
Increased flow rate	27	30	0.9	1377
Excessive flow rate	27	60	0.45	2755

According to this, fluid flow is described with the continuity equation:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \tag{3}$$

and Navier-Stokes equations:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \rho(\vec{u} \cdot \vec{\nabla})\vec{u} = -\vec{\nabla}p + \mu\nabla^2\vec{u} + \rho\vec{g} \tag{4}$$

where ρ is fluid density, $\vec{u}$ is fluid velocity, p is pressure, μ is fluid dynamic viscosity and $\vec{g}$ is gravitational acceleration.
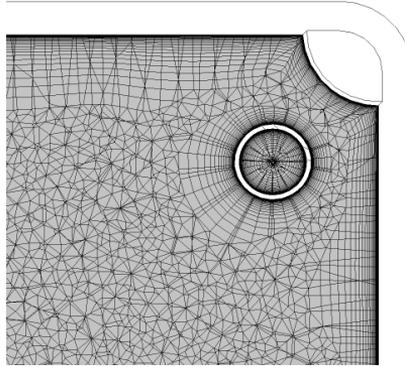
Figure 3: Mesh detail.

Following the laminar flow regime in the hydraulic tank pipes, a tetrahedral mesh was used for simulation with 2,675,435 elements, minimal orthogonality of 0.0499 and an aspect ratio of 6708. The mesh detail is shown in Figure 3.

5 Results

Figure 4 shows streamlines in the hydraulic tank for three analysed flow cases. It is evident that an increase of flow rate extends the path (trajectory) of the fluid element. Despite the laminar flow regime, it is evident that increased and excessive flow rates cause more vorticity.

Recommended $Q\mathrm{p} = 6 \ \mathrm{l/min}$	
Increased $Q\mathrm{p} = 30 \ \mathrm{l/min}$	
Excessive $Q\mathrm{p} = 60 \ \mathrm{l/min}$	
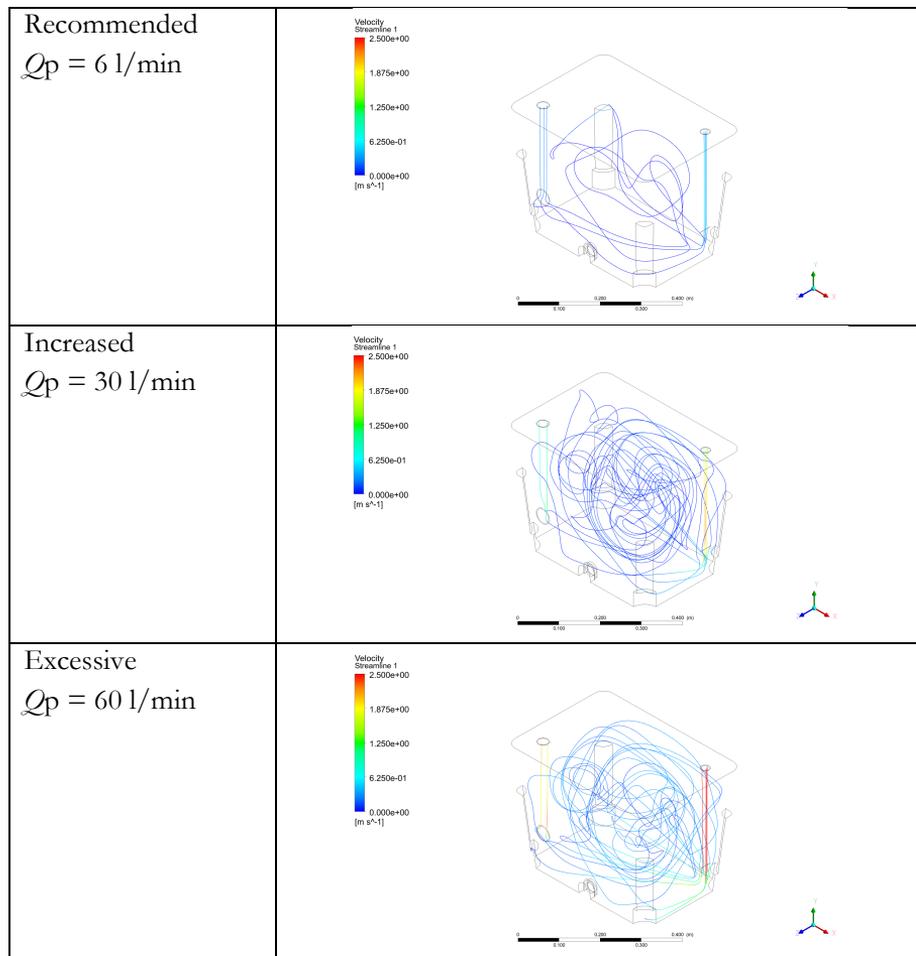
Figure 4: Streamlines in the hydraulic tank for the analysed flow cases.

Figure 5 shows the velocity vector field for all the analysed flow cases. It is evident that the vector field remains similar, which is a logical consequence of a laminar flow regime. The velocity magnitude and gradients are higher when flow rate is increased or excessive.

Recommended $Q_p = 6$ l/min	
Increased $Q_p = 30$ l/min	
Excessive $Q_p = 60$ l/min	
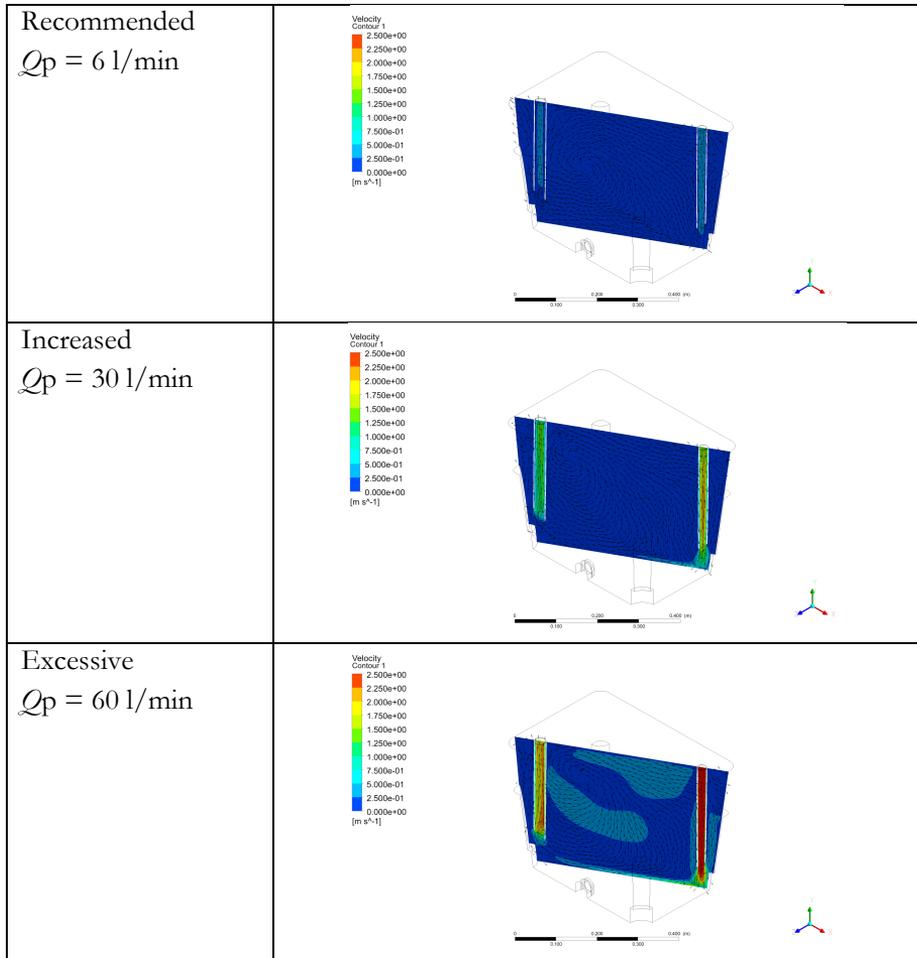
Figure 5: Velocity field for the analysed flow cases.

Figure 6 shows the shear strain rate at the tank bottom. Following the velocity field, it is evident that an increase of flow rate in the hydraulic tank leads to higher shear strain rate on the walls. According to this, increased flow rates result in poorer excretion of gas bubbles and poorer sedimentation of solid particles. This effect seems to have similar consequences as viscosity decrease of the fluid.

Recommended $Q_p = 6$ l/min	
Increased $Q_p = 30$ l/min	
Excessive $Q_p = 60$ l/min	
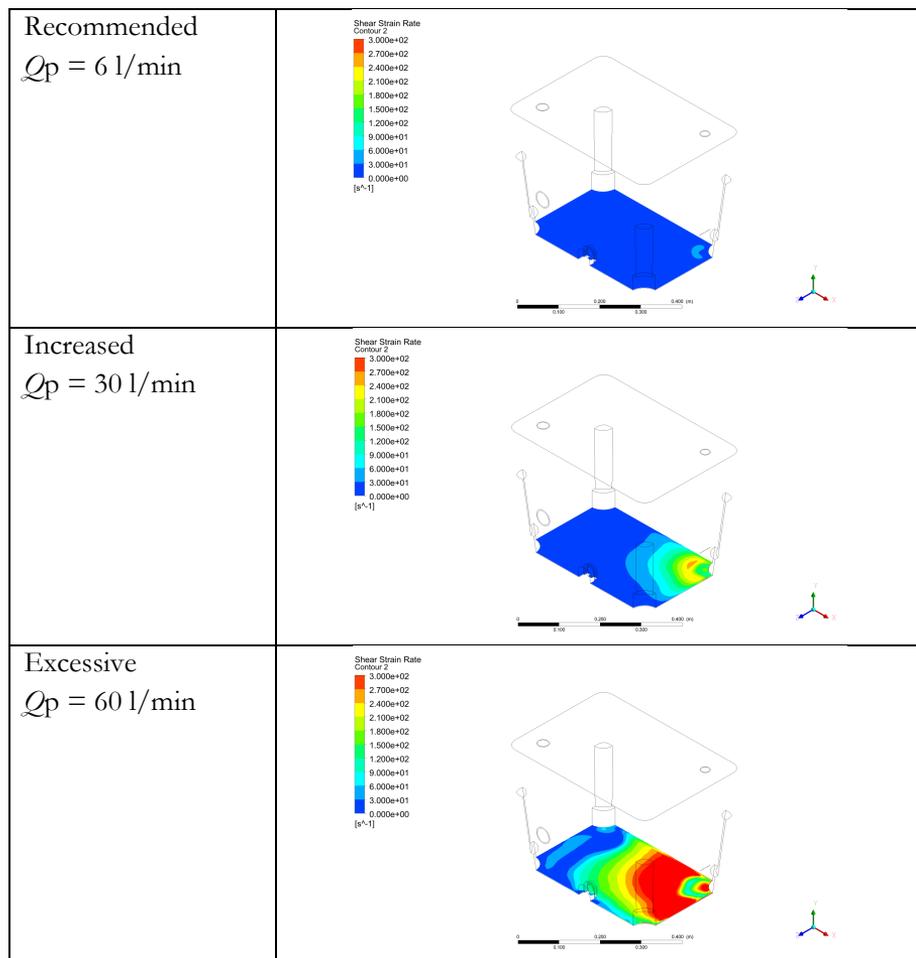
Figure 6: Shear strain rate at the tank bottom for the analysed flow cases.

5 Conclusions

The presented study, based on an appropriate model and simulation, deals with the flow conditions inside a hydraulic tank. As an example, a smaller 30-litre aluminium tank was used, and mineral hydraulic oil as the most used fluid.

At the forefront of the discussion is the impact of the relationship between tank size and pump flow. Three typical cases were considered. In the first case, the size of the tank was determined according to a recommendation that usually ensures optimal flow conditions. In the second and third cases, the influence of increased and excessive pump flow in the same large tank is shown. The latter may be due to an error - inappropriate selection of tank size according to the pump flow, or due to a purposefully selected smaller tank, as in the case of tribological tests with pumps. Similar conditions can also occur in the case of speed-controlled hydraulic pumps. The obtained insight into the current conditions inside the tank enables a more precise selection of the appropriate tank size or the use of a suitable tank design.

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