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CFD analysis of pressure variations on the waste valve of a hydraulic ram pump

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Abstract. Hydraulic ram pumps were invented around 1775 and arouse interest due to one of its main characteristics: to elevate a fluid to considerable heights using its own kinetic energy without using a power source external. This is due to the abrupt closing of the waste valve during the fluid flow, causing the phenomenon known as water hammer, which induces the opening of the discharge valve, leading the fluid to the accumulator and then raising it. Currently, computer simulation of fluid dynamics carried out studies and experiments in various components, helping to increase efficiency and consequently the field of applications of this equipment. However, no much research has been done on the waste valve, one of the main components of the hydraulic ram pump and responsible for the phenomenon on which its operation principle is based. Then, this study aims to determine the waste valve influence on the total efficiency of a hydraulic ram pump and thus, propose design changes to improve pump performance. For this, computational fluid dynamics (CFD) analyzes were performed using Ansys Fluent software through the pump body. The pump geometry chosen was based on a real hydraulic ram and the discharge valve is considered closed in order to simplify the simulation. It is already known that the pressure on the bottom surface of the waste valve interferes with its closing speed, with higher pressures resulting in higher speeds and increased pump efficiencies. To increase this pressure, simulations were performed with the valve originally plane, changing its geometry to the concave shape, also varying the inlet pressure for both geometries and considering two cases of height difference. The simulations resulted in a higher pressure on the surface of the plane valve for the lowest inlet pressure and, on the other hand, in a greater pressure on the surface of the concave valve for the highest inlet pressure, thus showing that the proposed change in geometry would result in positive effects for greater fall heights.

Keywords: Waste valve geometry, inlet pressure, performance.

1. INTRODUCTION

Water is one of the most important riches for human life and indispensable in the agricultural segment, being a vital natural resource in the entire ecosystem. In addition, it is fundamental to the development of the global and regional economy, making social sustainability directly dependent on this resource. Several factors are influenced by insufficient water supply, among these, we can mention population growth, agriculture, among other economic activities (Jia *et al.*, 2017). Considering this, it is essential to conduct investment and water yield planning in related sectors, in agriculture, energy, and industry, with the aim of maximizing economic results (Karayel *et al.*, 2017). Therefore, the use of a piece of equipment called a "Hydraulic Ram" is one of the ways to carry out water transportation in several applications, including agriculture. The "Hydraulic ram" ("Fig. 1") is a mechanical device to pump water automatically, that uses a small elevation of a water column to lift part of the fluid into a greater height (Abate, 2000). The main advantage is

that the only mobile parts are two valves, thus being mechanically simpler, with minimal maintenance requirements and providing a lengthy service life (Rojas, 2002).

The operation principle is based on the phenomenon called “Water Hammer”, where the energy of the inlet flow can be transferred to the delivery flow. Initially, the waste valve is found open, by implication, the water flows through the tubulation (through a filter) from the source of the water (Carlsson, 2016).

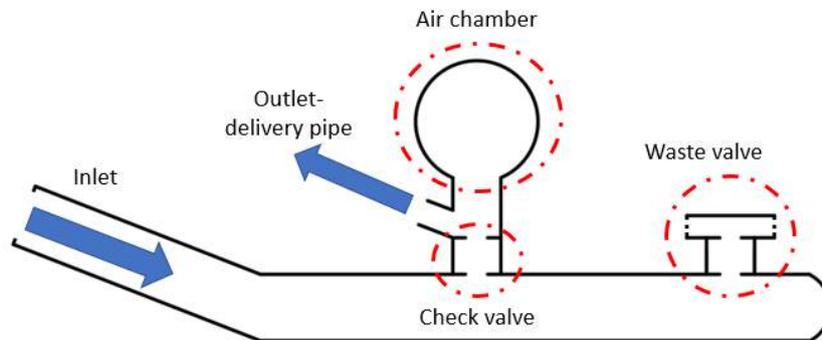


Figure 1. Hydraulic ram pump illustration. Source: Authors.

As the flow accelerates, the hydraulic pressure under the waste valve and the static pressure in the mechanism body, will increase until the resulting forces surpass the force (weight or of a string) that keeps the waste valve open and then, start to close it. As soon as the waste valve starts to close, the water pressure rapidly increases, closing the valve abruptly. As the water column in the inlet tube is not able to leave through the waste valve, this keeps causing a considerable increase in the pressure that forces the opening in the check valve (Carlsson, 2016). Once the pressure exceeds the capacity of the static discharge, the water will be forced to start raising through the discharge pipe. The air contained is simultaneously compressed into a pressure that exceeds the outlet pressure. Afterwards, the column of water stops and the static pressure decreases to levels next to the pressure in the supplying period. The check valve closes when the pressure in the air chamber exceeds the pressure in the recipient, with the cycle restarting after (Carlsson, 2016). In “Fig. 2” is represented a commercial model of hydraulic ram.



Figure 2. Commercial hydraulic ram. Source: (Marumby, 2014)

The faster the waste valve closes, greater is the frequency with which that occurs, resulting in a better performance, however in a smaller elevation outflow (Rojas, 2002). Therefore, when the objective is to increase the efficiency regardless of this flow, modifications can be made to the waste valve to increase its closing speed, as long as these are not related to the reduction of its course, as this usually decreases the escape flow and the drag force on the valve, consequently reducing its closing speed (Abate, 2000).

In the literature, evaluation and optimization reports of the performance about hydraulic rams can be found. Among them, analysis of the influence of inlet pipes material in the performance (Abate, 2000), under different dropping heights, concluded that PVC pipes are more efficient until 4,2m, and beyond that, galvanized steel pipes are more efficient, for the analyzed hydraulic ram. Similarly, an evaluation also assessed the performance variation under different materials and dropping heights, using an electrovalve directed by a computer in the place of an waste valve, to vary the closing time electronically (Rojas, 2002). This way, for the hydraulic ram considered, the author obtained a maximum efficiency of 62% for a pulse of 0.2 seconds, an inlet pressure of 72 kPa, using a PVC inlet pipe.

However, investigations focused on the behavior of the performance with the variation of the geometry of the waste valve cannot be found in the present literature. Therefore, a CFD (Computational Fluid Dynamics) simulation of a “hydraulic ram” for different input pressures was created. The draining properties were calculated through the simulation, emphasizing the pressures and speeds during the first stage of the operation cycle. Considering this, the waste valve geometry was modified aiming for a greater pressure over its inferior surface and, consequently, a greater closing speed to achieve an increase in the efficiency.

2. THEORETICAL REFERENCE

The historic development is discussed with some detail, aiming to verify which research fronts still need investigation. Reports points that Whitehurst built the first hydraulic pump of the “ram” kind in 1775, which worked manually through the act of opening and closing a valve similar to a faucet. The mechanism was able to rise water to a height of 4,9m. Afterwards, Montgolfier invented the first automatic hydraulic ram in 1796, to risewater in his paper factory. Pierce improved Montgolfier’s work in 1816, when conceived a retention valve to induce air to the air chamber, which had 300 mm in diameter. This pump raised water with a flow of 1700 l/min to a height of 48m (Ferreira, 2016).

Four years after, in 1820, Easton and James started the first large scale production for commercial purposes. Their hydraulic rams were used to supply water to big field houses, yards and villages, applications still used nowadays. In 1957, Calver assessed the characteristics of performance of the hydraulic ram and made the next improvement (Abate, 2000).

The possible independent variables of the installations of the hydraulic ram were considered and with a few conjectures its numbers were reduced using dimensionless parameters such as Reynold’s number, Froude’s number, Mach’s number and the coefficient of friction of the fluid. It is known that the Reynold’s number was efficient in practical dimension machines and that it exists a range in which Mach’s number has little influence. Froude’s number was considered the standard to define the possibility of the operation of the ram, the exit of the fluid and the efficiency of the ram in relation to the air chamber (Carlsson, 2016).

However, only in 1902 Allievi developed the water hammer theory, postulating tables for the pressure peaks in the section of the waste valve, for the occurrence of its uniform closing. Over time, the hydraulic transient was developed and the theory studied until resulting in the equations of mass and momentum (Ferreira, 2016).

According to Nigiz *et al.* (2017), for sustainable development to be achieved, sustainability of natural resources is necessary. Water resources are extremely important for the ecosystem (Işık and Çalıseki, 2017). Hatipoğlu *et al.* (2018), conducted a feasibility study of a project to invest in “hydraulic ram” type pumps, considering this as an environmentally friendly water pumping device, on account of not consuming fuel and electricity.

Asvapoositkul *et al.* (2019) states that for a hydraulic ram pump to be economically competitive, a study of performance and improvements in these devices is needed. For this to be possible, one needs to understand the parameters used for hydraulic ram pump (HRP) manufacturing. The author also conducted experimental tests with HRPs, varying some factors independently, concluding that an increase in waste valve beats tends to decrease the supply flow rate and delivery flow rate, but increases the overall efficiency of the equipment.

2.1 Water Hammer

Any perturbation or alteration, planned or accidental, in the pipes average flow will lead to pressure waves through the system. As the waves propagate, they create conditions for transitional flow pressure. Potentially, these transient conditions can generate severe consequences if not treated appropriately through analysis, conceptualization and appropriate operational considerations (Abate, 2000).

For example, when a valve starts to close, the pressure increases until it is completely closed. Depending on the necessary time for the valve to close, the increase of the first pressure will have hit a position in space that will give the pressure a wavelength. When the valve is completely closed, the pressure hits its maximum, and the wave propagates itself forward to level the difference in pressure (Ferreira, 2016).

“Figure 3” represents an accelerated transitory flow of water over a filled up horizontal tube (Carlsson, 2016). The left extremity is a deposit with constant pressure and the right extremity is a closing valve situated in the end of the Figure. According to the stages: (a) A constant water flow propagates itself to the right of the Figure. (b) The valve closes instantly (without wavelength) and starts the water hammer phenomenon, which is illustrated by the starting of the pressure rising. (c) The positive water hammer propagates itself forward to level the difference in pressure. The negative water hammer travels in the opposite direction of the positive. (d) The pressure hits the deposit and reflect positively its return. (e) This one propagates itself back to the valve that is behind the initiated pressure. (f) The velocity of the flow is pushed in the opposite direction of the pressure when it propagates itself. (g) In the valve, the pressure will reflect negatively. (h) The pressure propagates itself again in the direction of the deposit. (i) With a negative pressure, the speed of the flow is going to be zero. (j) The negative pressure reflects again in the deposit. (k) The pressure goes back to its initial condition. (l) The flow starts with speed in the same direction as the negative pressure propagates itself.

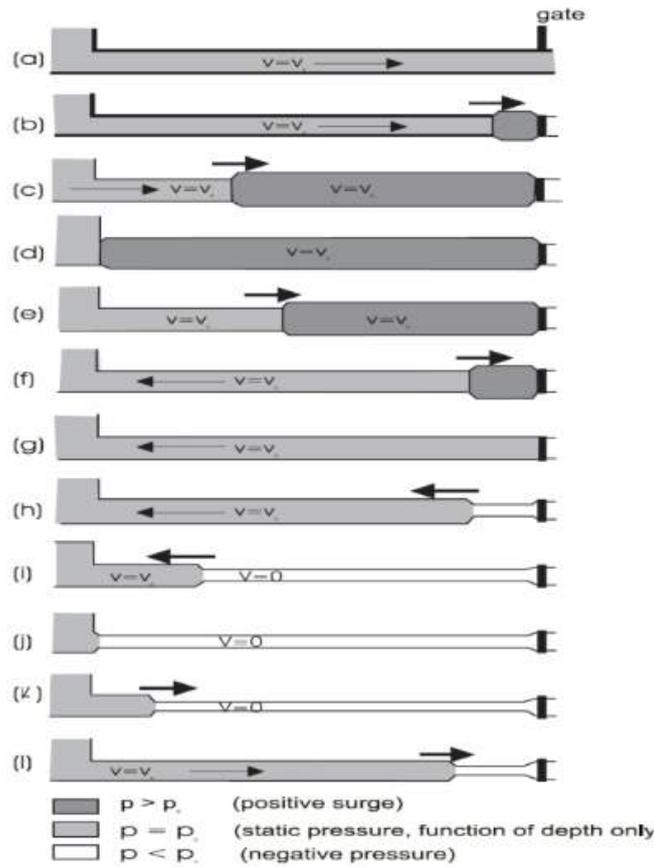


Figure 3. Transient Water Hammer. Source: (Carlsson, 2016)

The flow is called uniform when its velocity is constant in relation to the distance. When its velocity varies in relation to the distance, it is called non-uniform in some cases, but for a simplification of models, this speed is considered constant for a defined section. In the oscillating flow, for a considered period of time, the conditions repeats themselves periodically (Ferreira, 2016). According to Wylie and Streeter (1978), the terms transient flow and water hammer are used to describe the non-stationary state of the fluids in the pipes, that is, the properties vary with the time and space.

2.2 Mathematical modelling of the waste valve

According to Krol (1951), through a developed theory that satisfactorily agrees with the experiment, it's possible to foresee the behavior of any waste valve acting in an automatic hydraulic ram, provided that following four properties of some installation have been determined separately: (a) load loss in the transmission pipe; (b) load loss due to an waste valve; (c) the drag coefficient of the waste valve; and (e) load loss during the returning period.

To determine these properties is necessary to calculate previously the entry pressure P_i of the fluid in the hydraulic ram, which is given in relation to elevation ΔH , according to "Eq. (1)"

$$P_i = \rho g \Delta H \quad (1)$$

Once the system uses a sudden stop of the flow in the tube to create a high-pressure perturbation, the volumetric load of the transmission tube is given by the "Eq. (2)".

$$Q = \pi r^2 L \frac{n}{60} \quad (2)$$

Where Q is the outflow rate through the pipe, r is the radius of the pipe, L is the length of the pipe and n is the number of valve closings per minute. Besides that, the flow speed of the fluid in the conducted tube is given by the "Eq. (3)".

$$V_d = \frac{Q}{A_d} \quad (3)$$

In which V_d is the velocity of the fluid flow and A_d is the pipe area. To verify the nature of the regimes (laminar or turbulent), is necessary to determine the Reynold's number given by "Eq. (4)".

$$Re = \frac{Vd}{\nu} \quad (4)$$

In which d is the diameter of the pipe and ν is the cinematic viscosity.

The friction factor can be derived mathematically to a laminar regime, but no simple math relation to the variation of the friction factor with the Reynold's number is available to the turbulent flow. Besides that, the relative rugosity of the pipe (the proportion of the size of the imperfection of the surface to the internal diameter of the pipe) also affects the value of the friction factor (Ferreira, 2016). For smooth pipes with turbulent flows, this factor is given by "Eq. (5)".

$$f = \frac{0,316}{Re^{0,25}} \quad (5)$$

Where f is the fiction factor of the pipe.

According to Ferreira (2016), Darcy-Wersbach's formula is the base to assess the load losses in fluid flow inside tubes and conducts, and it is given by "Eq. (6)".

$$Hf = f \frac{L}{d} \left(\frac{V^2}{2g} \right) \quad (6)$$

In which g is the acceleration due to gravity, L is length of the pipe, V is the speed of the fluid and d is the diameter of the pipe. The speed of the fluid in connection T is obtained through "Eq. (7)".

$$V_T = \frac{Q}{A_T} \quad (7)$$

In which A_T is the section area of the pipe in the connection T. The load loss due to the abrupt increase in connection T is expressed through "Eq. (8)".

$$H_{LT} = \frac{(V_d - V_r)^2}{2g} \quad (8)$$

Other load losses, such as in valves, are usually expressed according to "Eq. (9)".

$$H_L = K_T \left(\frac{V^2}{2g} \right) \quad (9)$$

Once the manometric drop height H contributed to the acceleration of the water in the pipe, this acceleration is given by "Eq. (10)".

$$H - F \frac{L}{D} \left(\frac{V^2}{2g} \right) - \sum \left(K \frac{V^2}{2g} \right) = \left(\frac{L}{D} \right) \frac{dv}{dt} \quad (10)$$

The values of K and f can be found in default reference catalogs. Eventually, the outflow will be accelerated enough to start closing the waste valve. This occurs when the drag and pressure of the water are equal to the piston weight (Ferreira, 2016). The force of the drag is obtained through "Eq. (11)".

$$f_d = C_d A_v \rho \frac{V_o}{2g} \quad (11)$$

Where C_d the drag coefficient and V_o is the speed which the fluid drains through the transversal section of the waste valve. The force that accelerates the fluid is expressed through "Eq. (12)".

$$F = ma = \rho AL \frac{dv}{dt} \quad (12)$$

The pressure in dot is obtained dividing the F force in "Eq. (13)" by area A .

$$P_3 = \frac{F}{A} \quad (13)$$

The necessary power can be calculated according to "Eq. (14)".

$$P_t = \rho g Q h \quad (14)$$

In which h is the height of the piston over the vertical pipe that precedes the valve. In the end, according to Abate (2000), the efficiency of the hydraulic ram is calculated through the D'Aubuisson's relation, represented by "Eq. (15)".

$$\eta = \frac{qH}{(Q + q)H_r} \quad (15)$$

In which q is the repressed fluid outflow and H_r is repressed height.

3. Methodology

After describing the operation of a typical hydraulic ram installation, an analysis of the fundamentals of the waste valve and its phenomena, such as the water hammer, is made, being a pre-requisite to the adequate understanding of the hydraulic machine limitations.

The theory and the mathematical modeling presented previously, based on the application of the fluid mechanics general laws, were used in set with CFD analysis, considering a turbulent drain in permanent regime, using the SIMPLE algorithm, as well as specific entry data for the purpose of this study. Therefore, this study is based in computer simulations of the internal pressure and speed in the horizontal tube of the hydraulic ram, emphasizing the waste valve region, aiming to acquire the active average pressure in the inferior surface of the referred valve.

3.1 The CAD model used

To perform the simulation through the ANSYS Fluent software, was used a CAD model of a hydraulic ram (Farquhar, 2014), as presented by “Fig. 4” with an internal diameter of 106 mm and a length of 353 mm.

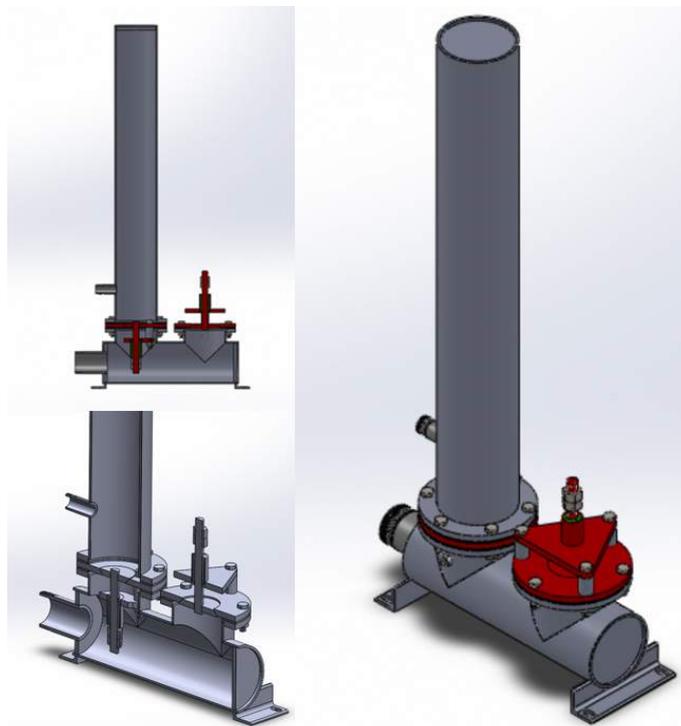


Figure 4. A CAD model of a hydraulic ram. Source: (Farquhar, 2014)

Besides the variations in pressure and speed occasioned by the difference in height, for both cases a simulation with different geometries for the waste valve were performed, looking for a greater pressure over it. The first model presents a flat geometry and the second model presents a concave geometry. Considering this difference on the contact area, different amounts of drag are found for each case, as shown in “Fig. 5”, consequently influencing in the result of the simulation.

Shape	Drag Coefficient	Shape	Drag Coefficient	Shape	Drag Coefficient
Sphere	0.47	Cube	1.05	Short Cylinder	1.15
Half-sphere	0.42	Angled Cube	0.80	Streamlined Body	0.04
Cone	0.50	Long Cylinder	0.82	Streamlined Half-body	0.09

Measured Drag Coefficients

Figure 5. Drag coefficient for different geometries. Source: Adapted from UMBC (2014)

3.2 Geometries for the waste valve

The geometry of the fluid domain was simplified, remaining only with an opening and an exit. The simplification occurred in the exit to the repression, in which represented a case where the repression valve was closed and, consequently, the waste valve was open. All these simplifications were done aiming to make easier the process of mesh generation.

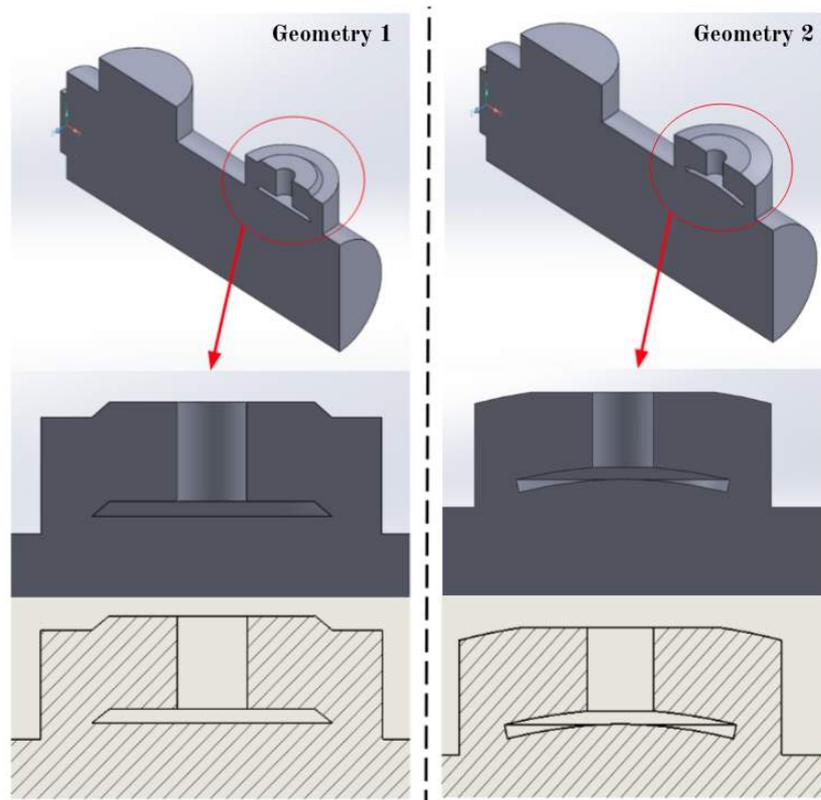


Figure 6. The valve geometries. Source: Authors

A simulation was performed for both valve geometries, considering two cases of drop height ΔH from the deposit in relation to the pump. Based on Abate (2000) and Rojas (2002) $\Delta H = 2,5m$ was defined for Case 1 and $\Delta H = 5m$ for Case 2, as shown in “Tab. 1”. The entry pressure for both cases were also calculated through “Eq. (1)”.

Table 1. Simulation Cases. Source: Authors

Case	ΔH (m)	P_{inlet} (kPa)
1	2,5	24,451
2	5	48,902

3.3 Mesh creation

The mesh test is one of the fundamental points to guarantee that the simulations are minimally numeric trustworthy. This test consists in increasing the number of mesh nodes until a stability in the required results for the simulation are reached. In this case, focus was in the pressure of valve inferior surface, aiming to avoid divergences to the real physical behavior and inconclusive results (Shende *et al.*, 2015).

A mesh model with tetrahedral elements was used to the fluid domain modelling. It was selected due to the adaptability to more complex geometries, while elements with other formats demand a greater refinement to avoid distortions (Shende *et al.*, 2015).

The mesh element of the valve body was refined to a size of 10 mm, with additional refining in the interest region of the waste valve. Meshes with the same characteristics were generated for both Geometry 1 “Fig. 7(a)” and Geometry 2 “Fig. 7(b)”.

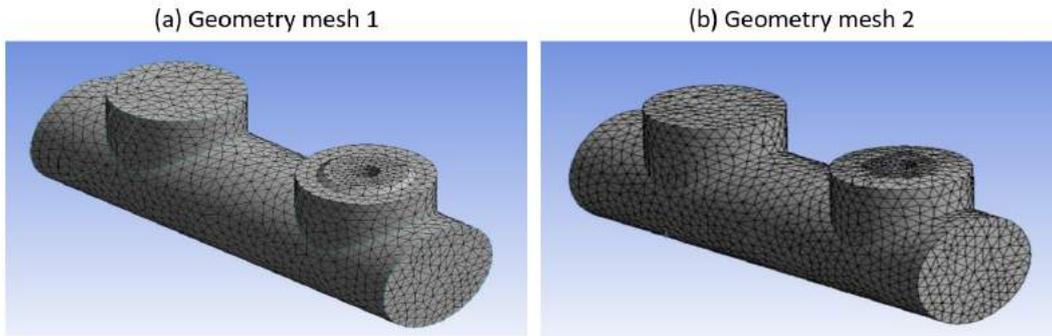


Figure 7. Geometric meshes. Source: Authors

4. RESULTS

Combining the geometries of Figure 6 with the cases of Table 1, simulations were created to find the velocities and pressures over the horizontal pipe of the hydraulic ram. The following results aim to allow the visual analysis of the speed and pressure profiles in the average plan of the fluid domain.

4.1 Velocity profiles in the average plan

“Figure 8” shows velocity profiles for both geometries and analyzed cases. In Case 2, for both geometries, a region in the inferior part of the horizontal tube appeared, below the waste valve, in which the velocity decreases in comparison to Case 1 because the inlet pressure for case 2 is greater than case 1 due to the higher drop height.

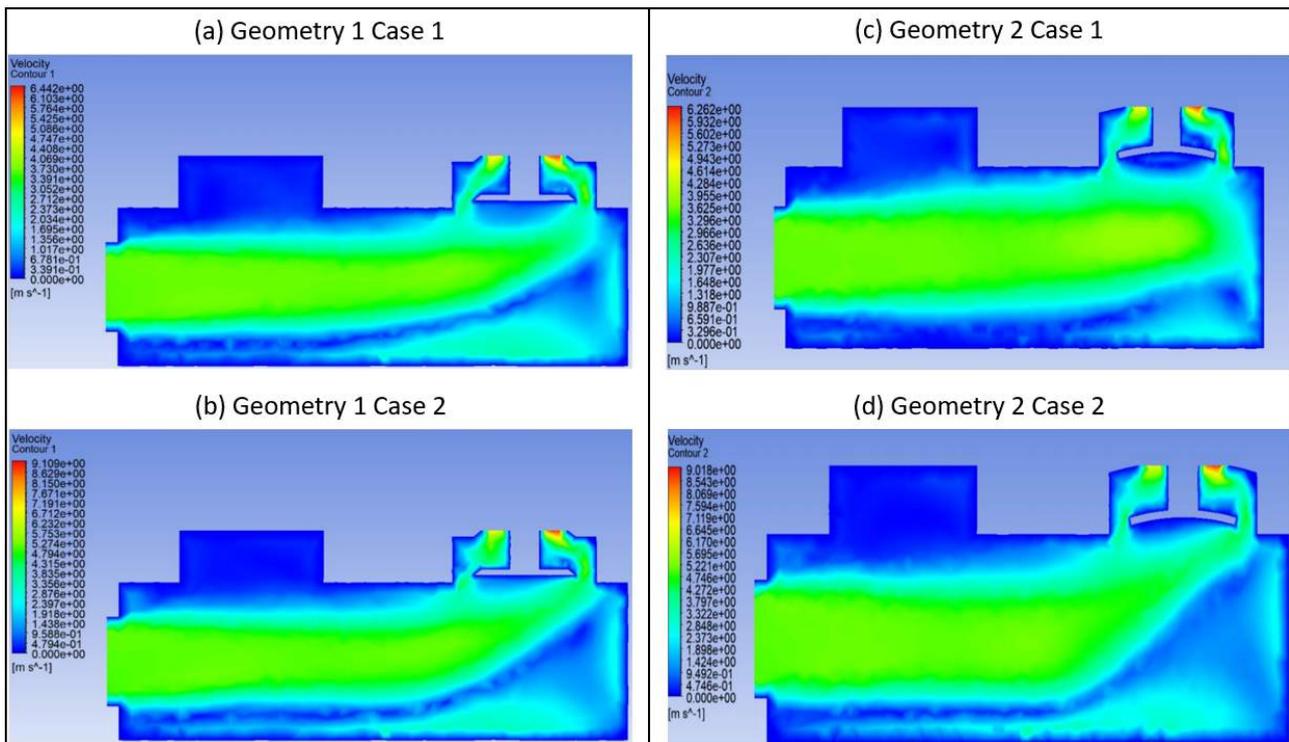


Figure 8. (a) Velocity for Geometry 1 and Case 1; (b) Velocity for Geometry 1 and Case 2; (c) Velocity for Geometry 2 and Case 1; (d) Velocity for Geometry 2 and Case 2. Source: Authors

4.2 Pressure profiles in the average plain

“Figure 9” exhibit the pressure profiles for both geometries and cases. Both geometries for Case 1 had a greater pressure concentration in the top region of the horizontal pipe, close to the waste valve. This pressure concentration is also affected by the turbulence that, increases for both geometries in Case 2 and corroborates with current situation, with the dispersion of the concentrated pressure, in comparison with Case 1.

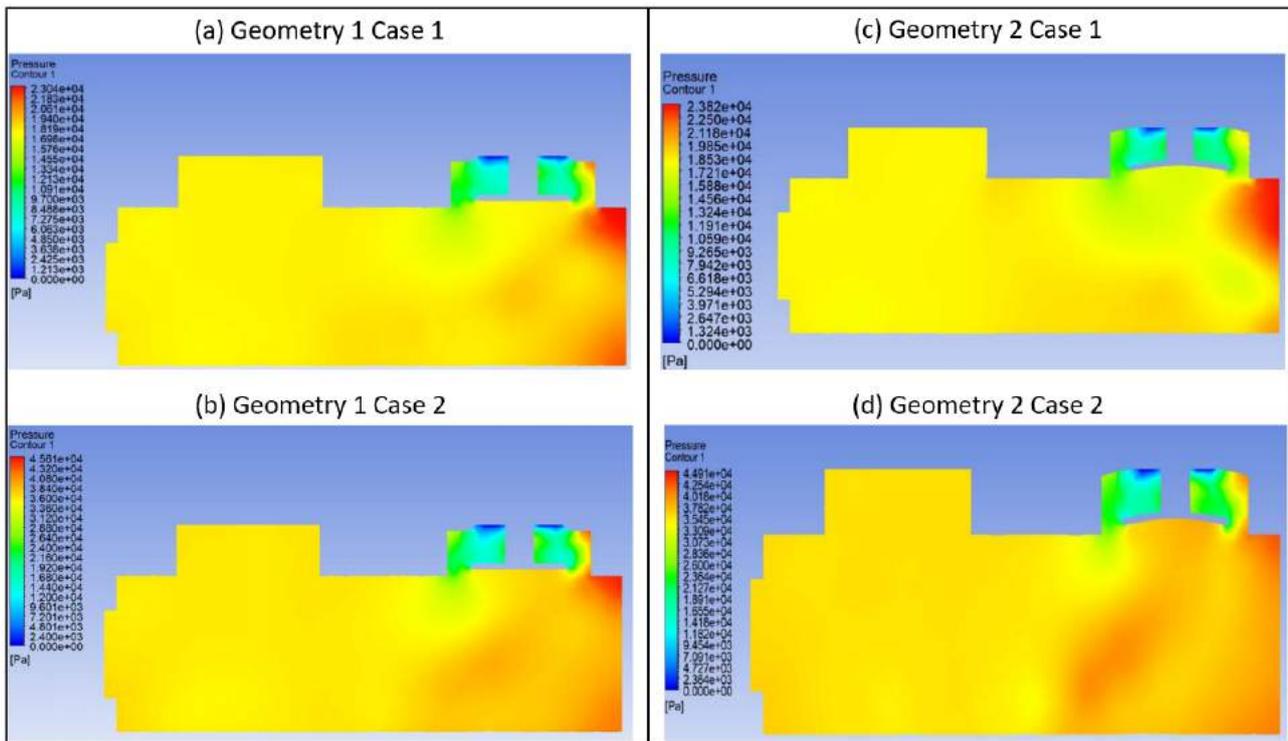


Figure 9. (a) Pressure for Geometry 1 and Case 1; (b) Pressure for Geometry 1 and Case 2; (c) Pressure for Geometry 2 and Case 1; (d) Pressure for Geometry 2 and Case 2. Source: Authors

4.3 Pressure in the valve surface

To summarize the information exhibited in Figures 9 to 16, “Tab. 2” presents the entry values and the main results found through the simulation.

Table 2. Results. Source: Authors

Geometry	ΔH (m)	P_{inlet} (kPa)	A_{valve} (mm ²)	P_{valve} (kPa)
1	2,5	24,451	1869,64	17,3
1	5	48,902	1869,64	35,7
2	2,5	24,451	1875,99	16,9
2	5	48,902	1875,99	36,8

Analyzing through Table 2, the pressure values in the lower surface of the waste valve, it is possible to observe that for Geometry 1 and inlet pressure of 24,45 kPa the value of the pressure in the valve is 17,3 kPa, whereas for Geometry 2 the same entry pressure was found lower, 16,9 kPa. For Case 2, with inlet pressure of 48,9 kPa, the pressures in the valve were 35,7 kPa and 36,8 kPa for Geometries 1 and 2, respectively, happening an increase in pressure over the surface of the valve of Geometry 2. This is due to the greater area of the lower surface of geometry 2 (concave) than geometry 1 (flat) of waste valve.

These values of pressure in the inferior surface are important to define the geometry of the waste valve, creating a possible relation with its closing speed and with the frequency of valve closing, once the frequency of closings increases the efficiency of the system.

5. CONCLUSION

This study was performed aiming to compare the behavior of speed and pressure in the interior of the horizontal tube and in the inferior surface of the waste valve of the hydraulic ram, varying two parameters: the dropping height and the geometry of the valve.

It is possible to conclude that as observed for the Geometry 1, the pressure over the inferior surface of the valve was bigger for Case 1 and lower for Case 2, in comparison with Geometry 2. The probable causes are the face areas for Geometry 2, which is a bit bigger in comparison with Geometry 1, as well as the variation of inlet speed for fluids between

the simulated cases.

According to the simulated results, these parameters have a significant effect in the fluid flow. For cases that have a lower drop height, there was no significant difference in pressure between the 2 geometries, but for cases where there is a higher drop height, geometry 2 obtained a higher pressure in relation to geometry 1, causing more closes per minute increasing system performance.

The methodology using CFD Ansys Fluent software proved to be effective in finding the pressure values existing in the lower region of the waste valve, validating the comparison of results between different cases and geometries. For future research, can be proposed a study regarding the closing time of the waste valve, as well as the frequency in which the closings occur to find efficiency, using the pressure values found as result of the present investigation.

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