Investigation of Water Flow Characteristics around the Waste Valve by Addition of Spacer Geometry on the Tee Brach of the Hydraulic Ram Pump Body

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Abstract: *A waste valve is a crucial component in the operation of a hydraulic ram pump (HRP) as the sudden closure of the waste valve induces the phenomenon of water hammer pressure. The flow beneath the waste valve exhibits uneven distribution, which causes damage to the waste valve. To improve flow uniformity, a spacer is added at the branch tee of the pump body, which serves as the seat for the waste valve. Simulations were conducted in the area beneath the waste valve with and without the addition of a spacer. The spacer heights were varied as: 0.25D, 0.5D, 0.75D, 1D, 1.25D, 1.5D, 1.75D, and 2D, where D is diameter of 2.5 inch. The Computational Fluid Dynamics (CFD) method was used to simulate fluid flow in the HRP with the waste valve open and the delivery valve closed. The addition of a spacer improved the uniformity of flow beneath the waste valve and influenced pressure distribution. Spacers with heights of 1.25D and 1.5D provided the most uniform pressure distribution beneath the waste valve. Therefore, it is recommended to append a spacer with a height of 1.5D in the construction of the HRP body.*

Keywords:Hydraulic ram pump, CFD, fluid flow, pressure, spacer*

I. Introduction

1.1. Introduction

The HRP is one of the many types of pumps used to transfer water from a lower elevation to a higher one [1]. The HRP is a pumping system that can operate without using electrical power as its energy source, insteaduses kinetic energy derived from the water flow within the pump itself [2]. The HRP was invented more than two centuries ago and is still in use today. The first HRP was invented by John Whitehurst in 1771, and it was later patented in 1809 by J. Cerneau and S. S. Hallet in New York [3]. The HRP is a pumping system that operates on renewable energy principles [4].

AHRP, which is an abbreviation for a HRP, is a pump whose energy or driving force comes from the pressure or impact of water [5]. Therefore, no electricity or other fuel sources are needed as its driving energy [6,7]. The HRP simply consists of a drive pipe, pump body (tee and elbow), waste valve, delivery valve, air chamber, and transmission pipe [8]. The working principle of the HRP is the conversion of kinetic energy from the water flow into dynamic pressure, which is known as water hammer pressure [2]. When the water flow is suddenly stopped, it generates a surge of pressure in the water flow, which is referred to as water hammer pressure or water hammer force [9].

The HRP body is equipped with a waste valve and a delivery valve [10], which are expected to generate high pressure due to the water hammer effect. Several studies related to the pump body have been conducted, such as by Hanafie and Longh [11], who stated that the cross-sectional area of the pump body should be twice the cross-sectional area of the drive pipe. Furthermore, Yang stated that the pump body affects performance; thus, based on their research results, they recommended not using a conical diffuser but a cambered diffuser with an angle between 25° and 90° [12]. Experimental evaluation showed that adding a short-cambered diffuser between the knee and the waste valve in aHRP increased its efficiency to 53 percent. Then, Guo proposed enlarging the system to reduce the head loss coefficient and drag coefficient [13], with a larger eccentric distance and higher velocity distribution uniformity for optimal design and performance analysis of the HRP system through numerical simulation and physical experiments.

The waste valve, where water hammer pressure occurs, is one of the components that frequently experiences damage [8]. To understand what happens, it is necessary to observe the flow pattern characteristics around the waste valve. The flow pattern characteristics in anHRP can be investigated using simulations with CFD (Computational Fluid Dynamics) software, such as Ansys Fluent [14]. Based on the general model of an existing HRP, it was found that the flow pattern beneath the waste valve is uneven.

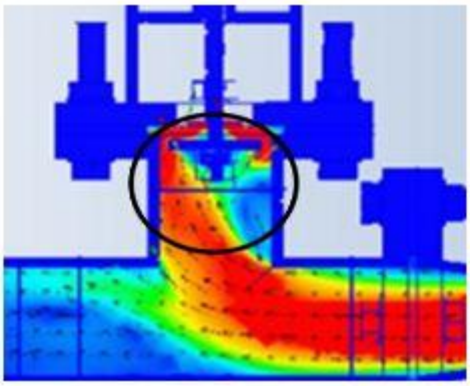


Figure 1. Flow pattern at the waste valve

This uneven flow pattern can cause different pressures on one side of the waste valve weight, which can result in a bending moment on the shaft and lead to shaft bending. Damage caused by the uneven flow pattern not only affects the waste valve shaft but also damages the top part of the waste valve due to the shaft's movement not following its intended path. Based on this phenomenon, adding a spacer or additional pipe on the tee branch of the pump body as a seat for the waste valve is expected to produce a uniform pressure distribution and flow pattern around the valve. This is done to minimize the bending moment on the waste valve shaft.

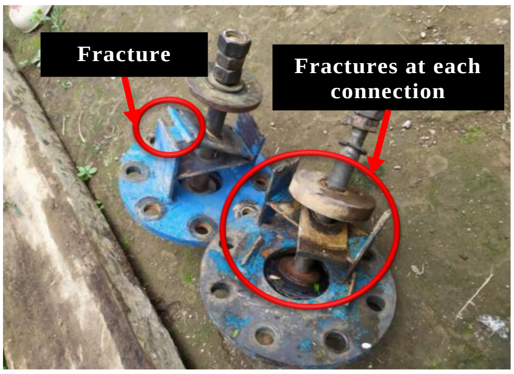


Figure 2. Fracture on the upper part of the waste valve

This research will simulate the effect of adding a spacer on the flow pattern and pressure around the waste valve of aHRP and determine the optimal spacer size to achieve uniform pressure and water flow patterns beneath the waste valve.

II. Research Methods

2.1. Research design

This research was conducted through testing using CFD analysis with Ansys Fluent software on a three-dimensional model design of anHRP installation, by adding variations in the length of the spacer between the pump body and the waste valve, such as in Fig. 3.The spacer size variations used in this study are based on the ratio of length (L) to diameter (D), where D = 2.5”. The spacer size variations in this study are 0.25D, 0.5D, 0.75D, 1D, 1.25D, 1.5D, 1.75D, and 2D.

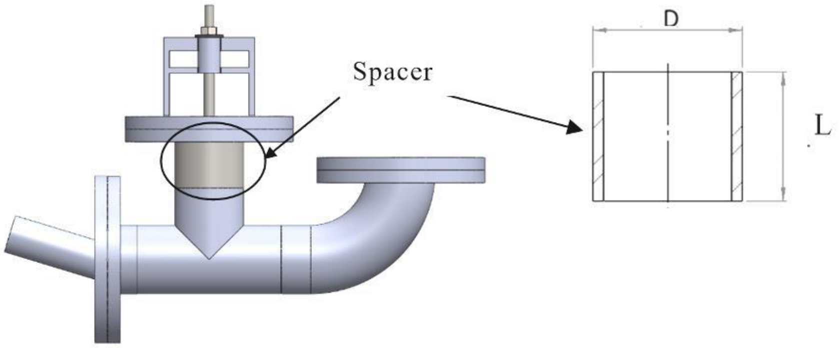


Figure 3. HRP with spacer

The size of the elbow, tee, and pipe in the pump body for this study is 2.5”.The inlet or drive pipe used has a diameter of 1.25” with a length of 100 mm from the pump body and forms an angle of 17˚ with the pump body. The diameter, length, and inclination of the drive pipe greatly affect the performance of the HRP [15]. Therefore, it can be concluded that the length and inclination of the pipe also influence the performance of the HRP.The waste valve outlet in this study has a diameter of 42 mm, where the waste valve opens fully at 7.5 mm.

During the meshing process, grid determination, number of nodes, meshing method, and boundary conditions were determined. It was observed that the minimum orthogonal quality and maximum skewness quality at the meshing stage already have good quality [16] as in Table I, and it meshing result is shown in Fig. 4.

Table I. Meshing Data

Statistic	
Meshing Method	*Tetrahedron*
Element Size	0,0007 m
Max Size	0,003 m
Defeature Size	0,00000635 m
Curvature Min Size	0,00000635 m
Curvature Normal Angle	12°
Growth Rate	1,2
Target Skewness	0,7
Target Orthogonal	0,2
Elements	6.493.718
Nodes	1.228.854

Minimum Orthogonal Quality	0,31807
Maximum Skewness Quality	0,68193

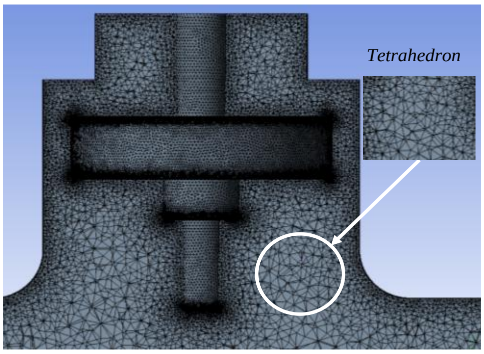


Figure 4. Meshing results on the geometric model

2.2. Simulation procedure

The simulation was conducted under steady conditions using FLUENT software, starting with the reading of the HRP fluid domain mesh model. Next, the setup of gravity factor activation was performed. The viscous model K-Omega SST was selected for this simulation. The K-Omega SST model was chosen because it effectively handles fluid components that interact with each other and can be used for Low-Re flows without additional damping functions. Its formulation can directly reach the viscous sub-layer [17]. The K-Omega SST model is an advancement of two models, K-Epsilon and K-Omega, and thus benefits from the advantages of the K-Omega model near walls and the K-Epsilon model in free flow regions. The K-Omega SST model uses two transport equations, one of which is the transport equation for K:

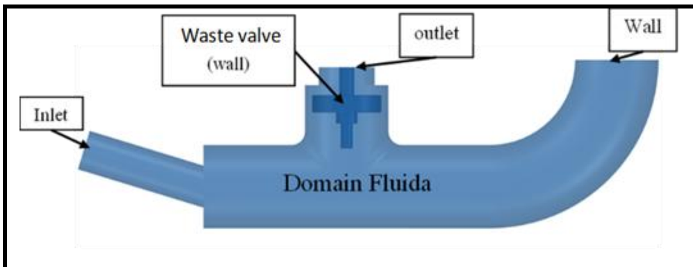
$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] \quad (1)$$

And the transport equation for ω:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial\partial}{x_j}\left[(\nu + \sigma_\omega \nu_T)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (2)$$

Next, the selection of the fluid material used and the boundary conditions in the simulation system were determined. The fluid used is water, which is assumed to be an incompressible fluid with a density of 998.2 kg/m³ and a viscosity of 0.001003 kg/m.s. The boundary conditions for this simulation can be seen in Table II.

Table II.Boundary Condition



(figure above)	➢ Inlet condition: Velocity inlet with a value of 0.8 m/s.
	➢ Outlet condition: Pressure outlet.
	➢ HRP walls: Set as walls with a no-slip condition.
	➢ HRP waste valve: Set as a wall with a no-slip condition

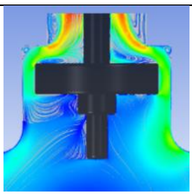
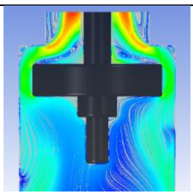
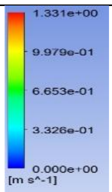
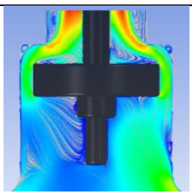
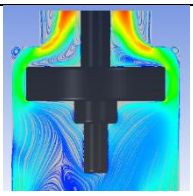
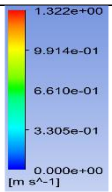
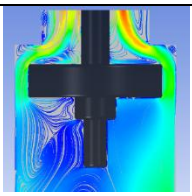
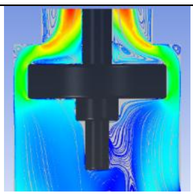
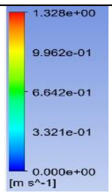
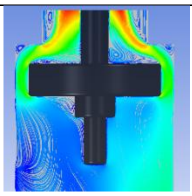
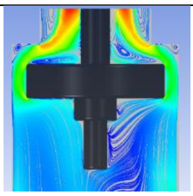
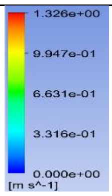
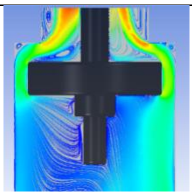
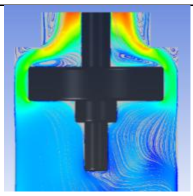
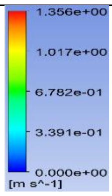
For the simulation solution method, the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) was chosen. This method is selected because it tends to be stable and convergent for many fluid flow problems; however, it requires many iterations to achieve convergence. The fluid domain is initialized using the hybrid initialization method, and the simulation is run with a convergence target of less than 10^{-4}.

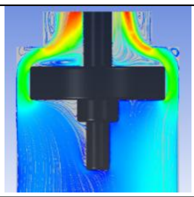
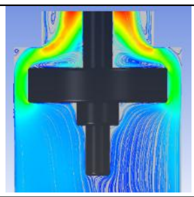
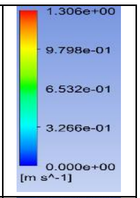
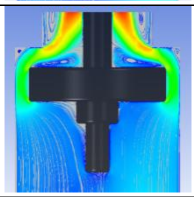
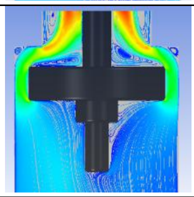
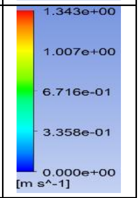
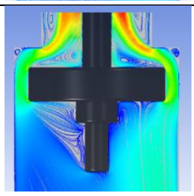
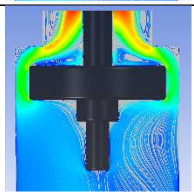
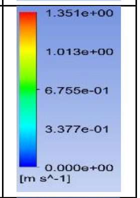
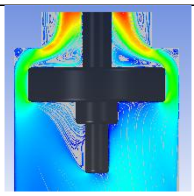
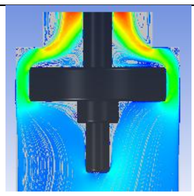
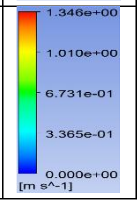
III. Results and Discussion

3.1. Streamline around the waste valve

In the simulation, it was observed that adding a spacer to the waste valve of the HRP affects the uniformity and stability of the flow. Without a spacer (0D), the flow pattern and velocity distribution were irregular, with significant turbulence around the waste valve. With the gradual addition of spacers ranging from 0.25D to 2D, the flow pattern showed increased uniformity and stability, particularly with the addition of 1.25D and 1.5D spacers. This improvement occurs because the spacer reduces the intersecting flows in the area around the valve, allowing for a more uniform upward flow beneath the waste valve and a more consistent flow separation above the waste valve. However, with the addition of 1.75D and 2D spacers, despite similar flow patterns to those with 1.25D and 1.5D spacers, significant turbulence was observed at the front of the waste valve, leading to a less optimal flow pattern, as shown in Table III.

Table III. Streamline around the waste valve

Spacer	Front view	Right view	Velocity range
0D			
0.25D			
0.5D			
0.75D			
1D			

1.25D			
1.5D			
1.75D			
2D			

It can be seen that the addition of a spacer improves the uniformity and stability of the flow around the waste valve, reduces turbulence, and provides a more even pressure distribution beneath the waste valve.

3.2. Pressure around the waste valve

The color range used in the simulation for pressure distribution was set from $7{,}6x10^2$to $1{,}002x10^3$ as shown in Fig.5.This was done to observe the pressure distribution for each spacer addition, allowing for a comparison of the distributions across the different studies.

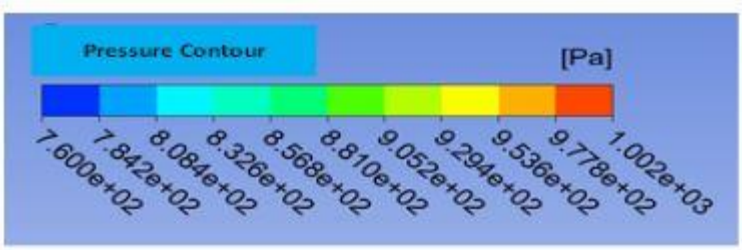
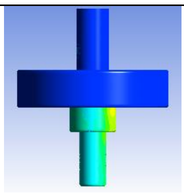
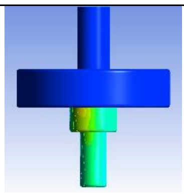
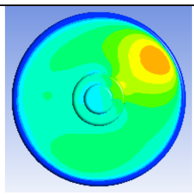
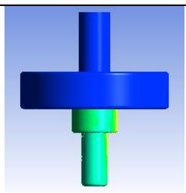
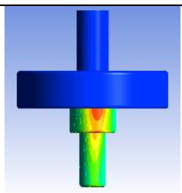
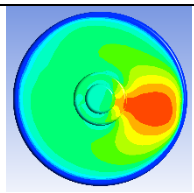
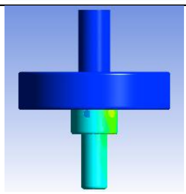
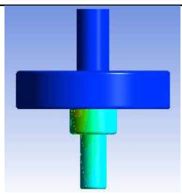
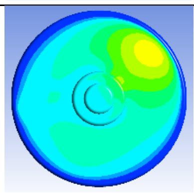
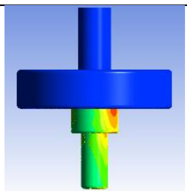
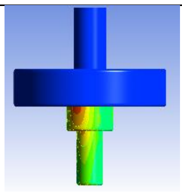
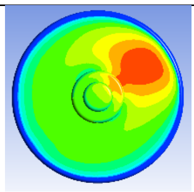
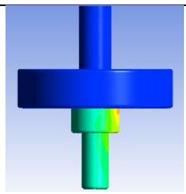
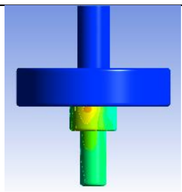
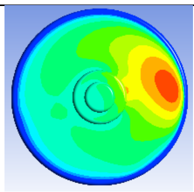
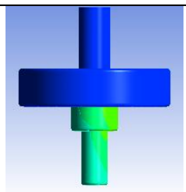
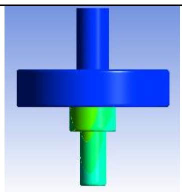
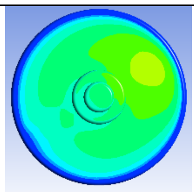
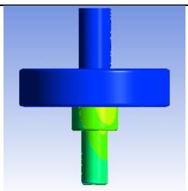
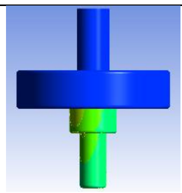
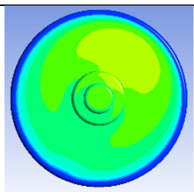
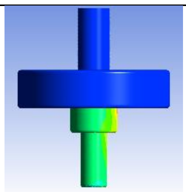
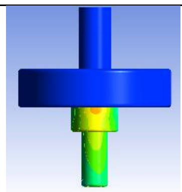
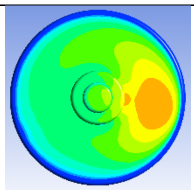
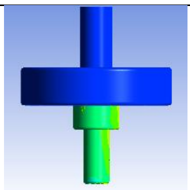
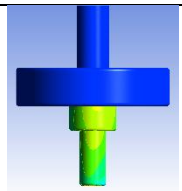
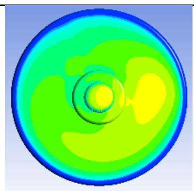


Figure 5. Pressure contour range

In the simulation, it was observed that the addition of a spacer to the waste valve of the HRP significantly affects pressure distribution, as shown in Table IV. Without the addition of a spacer, the pressure is concentrated in certain areas with significant differences in values, resulting in uneven pressure distribution. The addition of spacers from 0.25D to 1D still shows significant pressure differences. Pressure distribution becomes more even with the addition of 1.25D and 1.5D spacers, as seen in the equalization of pressure in areas that previously experienced excessive pressure concentration. However, with the addition of 1.75D and 2D spacers, the pressure distribution once again becomes uneven.

Table IV.Pressure distribution

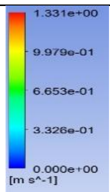
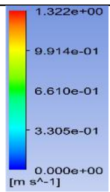
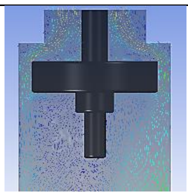
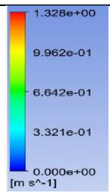
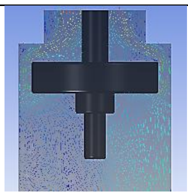
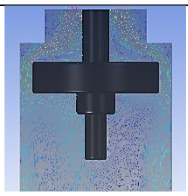
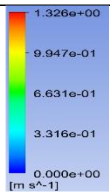
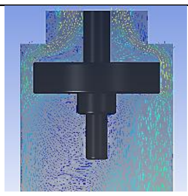
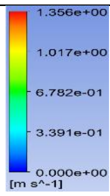
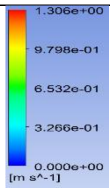
Spacer	Front view	Right view	Bottom view

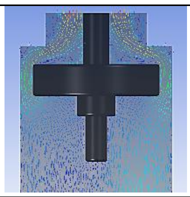
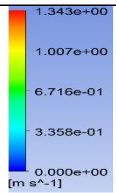
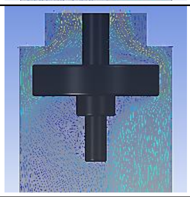
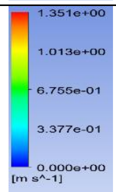
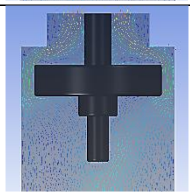
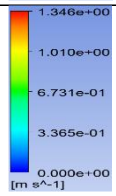
0D			
0.25D			
0.5D			
0.75D			
1D			
1.25D			
1.5D			
1.75D			
2D			

3.3. Vectors around the waste valve

Flow vector analysis simulations showed that adding a spacer to the waste valve of the HRP affects the uniformity of the flow vector direction, as shown in Table V. Without adding a spacer, the flow vectors appeared uneven, with some vectors moving irregularly at the bottom of the waste valve. With the addition of spacers from 0.25D to 1D, the direction of the vectors began to show uniformity, although some vectors were still irregular at the bottom of the waste valve. When a 1.25D and 1.5D spacer was added, the vector direction became significantly more uniform, with the vectors moving uniformly and no irregular vectors observed. However, with the addition of 1.75D and 2D spacers, the vectors at the bottom of the waste valve started to move slightly irregularly.

Table V.Velocity vector

Spacer	Front view	Right view	Velocity Range
0D			
0.25D			
0.5D			
0.75D			
1D			
1.25D			

1.5D			
1.75D			
2D			

This simulation shows that adding a spacer improves the uniformity of the flow vector direction around the waste valve, with the 1.25D and 1.5D spacers providing the most optimal results. With a more uniform flow vector direction, the distribution of forces acting on the waste valve can be more balanced.

3.4. Waste Valve Pressure Data Processing

In the simulation data of the pressure acting on the waste valve, it was observed that the highest force in the y-direction occurred with the addition of a 1.75D spacer. The smallest forces in the x and z directions were observed with the addition of a 1.5D spacer. The table includes negative values based on the three-dimensional coordinate field, indicating a direction opposite to x, y, or z. Ideally, the forces in the x and z directions should approach zero to minimize potential damage.

Table VI.Waste Valve Pressure Data

Spacer	***Force (N)***		
	x	*y*	*z*
0	0.036539228	087097691	-0.042256259
0.25	0.0024362047	0.89410022	-0.00050951247
0.5	0.016346952	0.86816463	-0.0011869782
0.75	0.0056390993	0.90158811	0.0040182069
1	0.0033063037	0.89317673	0.027699181
1.25	0.017827231	0.88337198	0.016371938
1.5	-0.0010002404	0.88023782	-0.00032238662
1.75	0.016546154	0.90437506	0.022344653
2	0.0017761682	0.89781355	-0.0079253913

In Fig.6, the trendline shows an increase with the addition of spacers, while in Fig.7, the trendline shows a decrease. This indicates that the addition of spacers tends to increase vertical forces while decreasing horizontal forces.

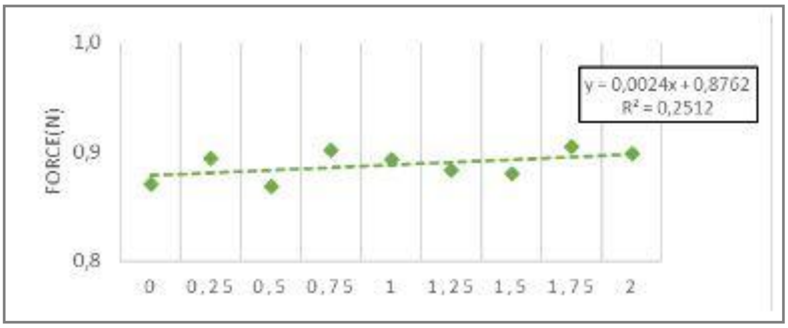


Figure 7. Force in the Y-direction

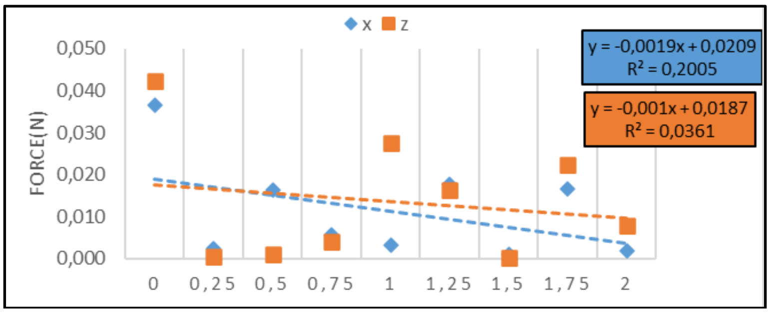


Figure 8. Force in the X and Z Directions

IV. Conclusion

Based on the results of the CFD simulation with the addition of spacer geometry to the body of the HRP using eight different spacer variations: 0.25D, 0.5D, 0.75D, 1D, 1.25D, 1.5D, 1.75D, and 2D, it can be concluded that adding a spacer affects the flow pattern and pressure distribution within the HRP. The flow pattern and pressure distribution change with each spacer increment, with 1.25D and 1.5D spacers resulting in an upward uniform flow pattern. This leads to increased pressure around the waste valve in the vertical direction and decreased pressure in the horizontal direction. This effect can minimize the differential forces that may cause bending in the waste valve components. The ideal spacer size in this simulation is 1.5D.

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