THEORETICAL EVALUATION OF THE HYDRODYNAMIC FORCES ACTING ON A BYPASS PIG INSIDE AN ACTIVE PIPELINE

Ramírez R. E., rramirez@ufrj.br
D. Sc. Student. Programa de Engenharia Mecânica. Instituto Alberto Luiz Coimbra de Pós-graduação e Pesquisa em Engenharia. COPPE. Universidad Federal do Rio de Janeiro. Centro de Tecnologia. Bloco I. Sala 101. Ilha de Fundão. CEP 21945-970. Rio de Janeiro. RJ. Brasil. Assistant Professor. Universidad Nacional de Colombia. Departamento de Ingeniería Mecánica y Mecatrónica. Ciudad Universitaria. Of. 453-401. Bogotá Colombia

Dutra M. S., max@mecanica.coppe.ufrj.br
Asociated professor. Programa de Engenharia Mecânica. Instituto Alberto Luiz Coimbra de Pós-graduação e Pesquisa em Engenharia. COPPE. Universidad Federal do Rio de Janeiro. Centro de Tecnologia. Bloco G. Sala 201. Ilha de Fundão. CEP 21945-970. Rio de Janeiro. RJ. Brasil.

Abstract. *Use of smart PIGs with bypass holes to maintain a controlled speed had been developed for use in gas pipelines. The goal is to maintain the PIG´s speed lower than the mean flow velocity for good performance of the electronic systems used to measure the state of the line. Some actual projects deal with developing of PIGs with speed control for liquid pipelines, in order to inspect and service "unpiggable lines" and flexible lines. A method is to use a variable area bypass, part of the liquid fluxes through it, if the bypass flow is increased the speed of the PIG decreases. A second method is the use of active mechanisms with legs or wheels to climb or to travel the line at controlled speeds, sometimes in opposite direction to the liquid flow. In both cases the dynamics of the PIG is function of the hydrodynamic forces between the liquid and the PIG. This work studies theoretically a proposed geometry of a PIG capable of to stay with very low or zero speed inside an active pipeline with oil flowing inside it. A PIGs with velocity control could apply maintenance operations on the pipe or improve the inspection operations in the line. The study is limited for the hydraulic variables near the PIG and forces actuating it. Data input are the pipe dimensions, flow velocity, liquid properties andt the proposed geometry of the PIG, the hydrodynamic forces and the pressure drop are calculated on the line for the work volume selected.*

Keywords*: Pig, oil pipeline, hydrodynamic forces, modeling, dynamics.*

1. INTRODUCTION

In gas pipelines, large variations of PIG speed are noticeable in inspection operations. Uncontrolled speeds induce errors in the analysis of the data stored by the inspection electronics; furthermore, the PIG can cause damages on the line by impact forces. Some PIGs models used in gas lines has speed control and are applied for inspection, the literature describes design and application cases (Nguyen et al., 2001, Frota et al., 2007).

Now, there are projects to design PIG with speed control for use in liquid pipelines like lines with oil derivates. One of the objectives of this project is to design a PIG moving at very low speeds or stop when the line is transporting products in normal conditions. Possible applications are to improve the inspection processes in specific zones of the line or apply maintenance operations inside the pipe.

It is studied a system formed by a pipe segment, a simplified geometry PIG and the fluid, specific characteristics of the elements are described in the next section. The PIG model has a cylindrical orifice coaxial with his body as shown in Fig. 1; it permits the flow and keeps the line operative.

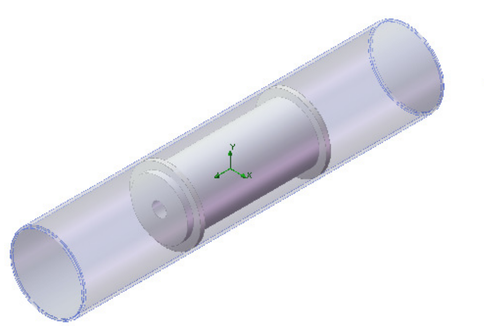

Figure 1. Diagram of the system

The objective is to know the hydrodynamic conditions near the pig body using a Finite Element Analysis (FEA) tool, under nominated boundary value conditions. A first variable of interest is the drag force on the PIG. A second variable is the pressure drop through the PIG.

With this forces, it can be designed the brake subsystems and calculated the energy losses. Furthermore, may be calculated additional power in the pumps in order to maintain the flow and can be made some considerations about efficiency and costs of the process. In third place, the PIG movements cause effects like vortexes and they can affect the line instrumentation measurements, changes on the PIG geometry or optimization design processes can decrease or remove these effects.

2. STUDIED SYSTEM

The system studied is formed by a pipe segment of 10 m with the PIG placed in it, a large pipe length decreases boundary effects near the PIG. The inner pipe diameter is 0.304 m (12 inches) and outer diameter is 0.324 m with a 10 micrometers roughness. The simulated fluid is gasoline with density $\rho = 747$ kg/m^3, dynamic viscosity $\mu = 0.00065736$ Pa*s at 288.8 K.

Typical pipeline mean velocities used in pipelines for this fluid are from 0 to 5 m/s, the study uses the next three values: 1 m/s to representing low flow, 3 m/s for medium flow and 5 m/s for high flow. The static pressure in a pipeline is variable with the distance to the pump station and the terrain altitude variations, typically varies from 0 to 10 bar, the study was made at constant static pressure in the outflow pipe ending with value $p_o = 506625$ Pa (aprox. 5 bar)

The PIG is modeled by a cylinder with a coaxial orifice, it has two external disks to simulate the typical polyurethane disks of an inspection tool, the flow goes by the orifice and there isn't flow between the cylinder and the pipe. The outer diameter of the cylinder is 80% of the pipe inner diameter and constant. The orifice diameter varies from 20% to 70% of the pipe inner diameter in 10% steps. The ratio of length of the pig body to pipe diameter is 2.0.

A CAD model of the PIG and pipe is showed in Fig. 1.

3. SYSTEM MODEL

The forces on the PIG are shown in Fig.2. The propulsion force *Fp*, the friction force *Ff*, pig's weight *W* and contact forces Fn.

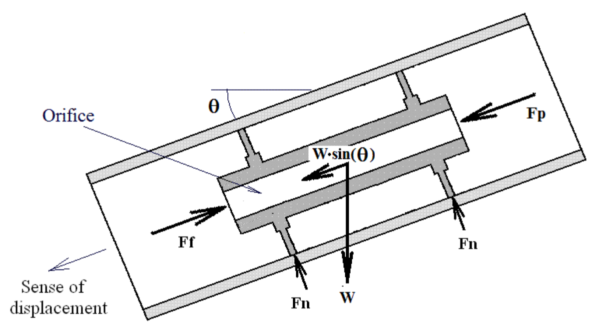

Figure 2. Forces on the PIG.

Fp is the equivalent force of the static pressures on the front and back faces of the pig plus the drag force on the inner surface of the orifice. The friction force of the disks on the inner surface of the pipe depends on the materials of disks and pipe, their static and dynamic friction coefficients and deformation of disks. The component of the weight in the axial direction is $W \cdot \sin(\theta)$ where the slope of the pipe is θ.

Equation (1) represents the dynamics in the axial direction of the pipe; m_p is the mass of the PIG and $\dot{V}_P$ is the time derivative of pig's velocity.

$$m_p \cdot \dot{V}_P = F_P - F_f + W \cdot \sin(\theta) \tag{1}$$

This work deals with evaluate ranges of F_p for variable flow conditions and for zero PIG speed, the other components of the dynamics will be studied in other works, all are part of the same project.

Computation of F_p is based in the solution of the differential form of the Navier-Stokes equations, shown in Eq. (2) using the Lomax et al. (1999) notation.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}=0$$
$$Q=\begin{bmatrix}\rho\\ \rho u\\ e\end{bmatrix},\qquad E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ u(e+p)\end{bmatrix}+\begin{bmatrix}0\\ \frac{4}{3}\mu\frac{\partial u}{\partial x}\\ \frac{4}{3}\mu u\frac{\partial u}{\partial x}+\kappa\frac{\partial T}{\partial x}\end{bmatrix} \tag{2}$$

In this equation u is the velocity, ρ the fluid density, p the pressure, e the energy and T the temperature. The next conditions were setting for the flow: Newtonian fluid, incompressible and adiabatic flow.

It was used a computational fluid dynamics (CFD) tool, based on the finite volume method to solve the system. The mesh cells are cubic type with a refinement in the fluid zones near the pig body like shown in the Fig. 3.

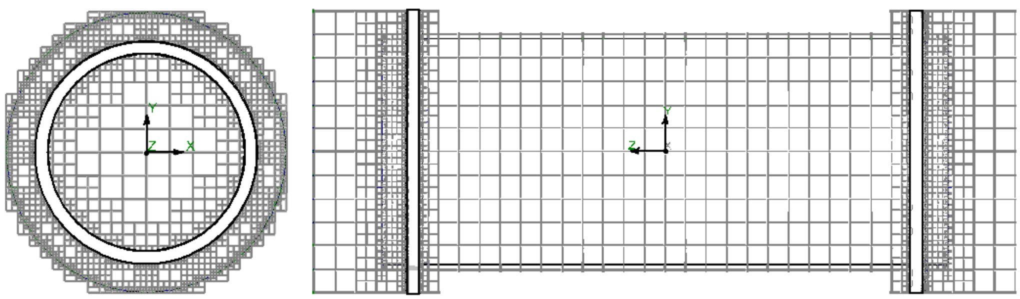

Figure 3. Used mesh.

4. RESULTS

For all studied cases the next variables and parameters are constants: pipe diameter and length, outer diameter and length of PIG body, outflow pressure and fluid properties. The numeric values were indicated in section 2.

For mean velocity of fluid at inflow were taken three representative values: 1 m/s, 3 m/s and 5 m/s. For each fluid velocity were calculated 6 cases for the ratio *DO/IDP,* where *DO* is the diameter of the central orifice in the PIG and *IDP* is the inner diameter of the pipe. Additionally, for each mean velocity was run a study for the pipe without PIG.

From the CFD tool after each calculation, are obtained directly the value of the drag and pressure force *Fp* on the PIG in the axial direction, and the static pressures at pipe inflow and outflow.

Equation (3) calculates the pressure losses in the pipe without PIG (Δp_{wop}) and Eq. (4) calculates the pressure loss due to PIG (Δp) for each case, pi and *po* are the static pressures at inflow and outflow, respectively. The subscript *wop* indicates the configuration without PIG.

$$\Delta p_{wop}=pi_{wop}-po_{wop} \tag{3}$$

$$\Delta p=pi-po-\Delta p_{wop} \tag{4}$$

The power loss due to PIG inside the pipe is calculated with Eq. (5), where V_f is the mean velocity of fluid and A is the inner area of pipe.

$$P_l=\Delta p*A*V_f \tag{5}$$

The numeric results are shown in Tab. 1, the force *Fp* is plotted in Fig. 4 and the power loss in Fig. 5. The larger results were eliminated from the figure because they exceed physical and economic conditions for any design project. Other data of interest for analysis are distributions of pressure, velocity fields and plots of trajectories of fluid particles, examples of these plots are shown in the Figures 6, 7 and 8, in all the figures the flow is from the right to the left.

Table 1. CFD results for propulsion force *Fp* and power loss P_l

Vm (m/s)	1		3		5	
DO/IDP	*Fp* (N)	P_l (kW)	*Fp* (N)	P_l (kW)	*Fp* (N)	P_l (kW)
0.2	20784	21.32	188796	582.08	531951	2730.23
0.3	3850	3.94	34165	105.08	95125	487.84
0.4	1164	1.19	10365	31.78	28729	146.65
0.5	401	0.41	3537	10.85	9805	50.21
0.6	151	0.15	1331	4.06	3687	18.72
0.7	59	0.06	527	1.63	1454	7.41

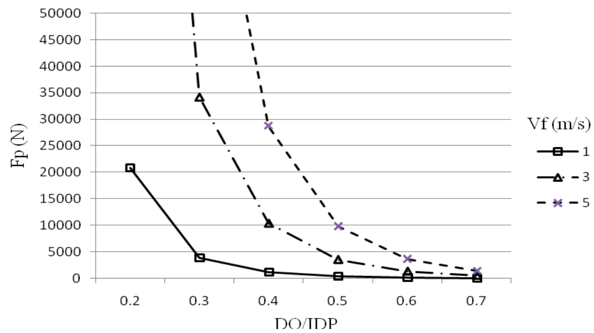

Figure 4. Force *Fp*.

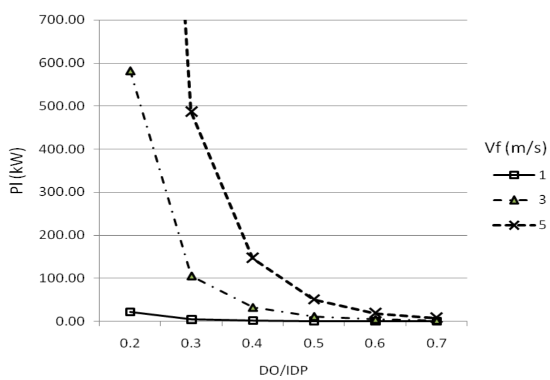

Figure 5. Power loss.

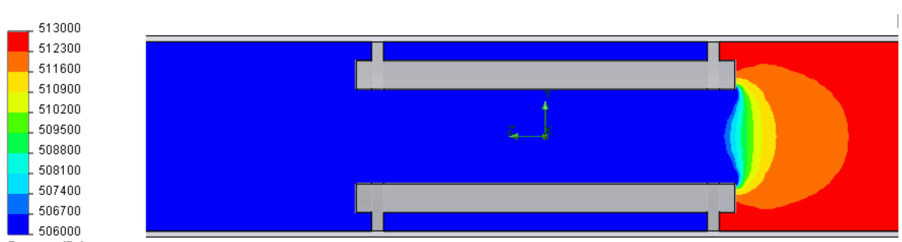

Figure 6. Pressure gradient for *Vf* = 1 m/s and *DO/IDP = 0.5*.

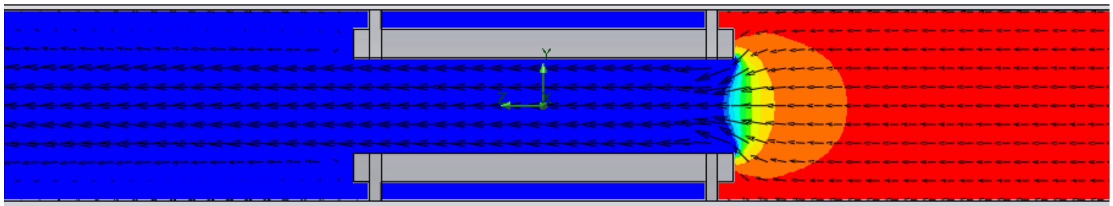

Figure 7. Velocity vector plot for *Vf* = 1 m/s and *DO/IDP = 0.5.*

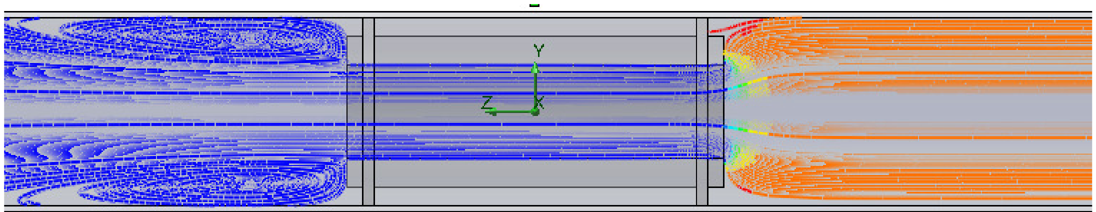

Figure 8. Fluid flow trajectories for *Vf* = 1 m/s and *DO/IDP = 0.5.*

5. ANALYSIS OF RESULTS

For greater orifice diameter the force *Fp* decreases, it is normal because the transversal areas of the PIG exposed to pressures are smaller and the orifice area is greater, the velocity inside it is smaller, then, the drag force decreases, too. In similar form, the power loss P_l deceases with greater orifice diameter, in this case for a bigger orifice the velocity inside is lower, reducing the turbulence and the fluid energy losses by friction.

The values of the variables obtained generate some constrains and criteria for later stages of the design process. A lower orifice diameter causes the PIG volume is bigger, with more space for sensors, actuators and electronics, but the larger forces generated make that the friction forces required to maintain the PIG stopped are larger, too. A constrain created is for example: to maintain the force *Fp* less than 1000 N, with velocities until 5 m/s, the minimum ratio *DO/IDP* is 0.5.

At the same time if *DO/IDP* has this minimum limit the power loss is limited less than 51 kW, this value is considered smaller if taken like a fraction of the power of typical pump units used in actual pipelines, the power of these units can be from of the order 10^3 to 10^5 kW (Flowserve, 2006).

6. CONCLUSIONS

The numeric results obtained vary according with previous behavior expected. The advantage obtained is the knowledge of magnitudes and ranges of variation.

The results allow the construction of a first design constrain and give some basis to progress in the conceptual design of the PIG.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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