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FLUID DYNAMICS ANALYSIS OF EMERGENCY FLOODGATE EQUIPMENT FOR FLOW CONTROL IN AN AUXILIARY SPILLWAY HYDROELECTRICAL DAM

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Abstract. *This paper presents an analytical study of the fluid dynamics conditions associated to the installation of emergency floodgate equipment - EFE, designed to interrupt and regulate the water flow in an auxiliary spillway hydroelectric dam, in an emergency situation. The auxiliary spillway system releases water in excess from the upstream side of a dam to its downstream side. It consists of a pipeline and floodgates to regulate its flow. The EFE is basically a steel structure containing hydraulic actuated butterfly valves and is planned to be installed nearby the pipeline intake, located at approximately 40 meters below reservoir level, where the flow regime is turbulent. Numerical simulations based on fluid dynamics models were developed and its results were used as design criteria for EFE dimensioning, so that cavitation forces and structural mechanical stresses could be estimated.*

Keywords: *floodgate equipment, auxiliary spillway, applied fluid dynamics, butterfly valves*

1. INTRODUCTION

Hydropower plants are built into the course of a river to produce electrical power. The most common type of hydroelectric power plant is an impoundment facility, which uses a dam to store river water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which in turn activates a generator to produce electricity. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

The hydropower house is the main part of a hydropower plant. It contains the turbines and the generators which produce electrical energy. The main control of the water discharge is also situated in the hydropower house. The water flow through the turbines can be regulated by adjusting the inflow to the turbines and by varying the angle of the turbine blades. If the water flow exceeds the maximal flow for which the turbines are set there are always alternative paths for the water flow besides going through the turbines (Gullhamn, 2004), denominated spillways.

A spillway is a structure used to provide the controlled release of flows from a dam or levee into a downstream area, typically being the river that was dammed. Spillways release floods so that the water does not overtop and damage or even destroy the dam. Except during flood periods, water does not normally flow over a spillway. A dam should be provided with either a single spillway or a service spillway-auxiliary spillway combination. Service Spillway is the principal or first-used spillway during flood flows. Auxiliary spillway is a secondary spillway designed to operate in general only during large floods.

Floodgates, also called stop gates, are adjustable gates used to control water flow in flood barriers, reservoir, river, stream, or levee systems. They may be designed to set spillway crest heights in dams, to adjust flow rates in sluices and canals, or they may be designed to stop water flow entirely as part of a levee or storm surge system. In the case of flood bypass systems, floodgates sometimes are also used to lower the water levels in a main river or canal by allowing more water to flow into a flood bypass or detention basin when the main river or canal is approaching a flood stage. Floodgates and fuse plugs may be designed into spillways to regulate water flow and dam height. There are mandatory guidelines for the design of dams (Eletrobras, 2003; Freckleton, *et al.*, 2011; Min. da Integração Nacional, 2005; New York State Dept. Environmental Conservation, 1989; US Dept. of Energy, 2010; Wilde and Johansson, 2013).

In the present work a fluid dynamic model is developed to describe and calculate the forces acting on the installation of a butterfly valve used to control the flow rate on a spillway. It was demonstrated that cavitation may occur during the installation and operational procedure.

2. OPERATIONAL SCENARIO

2.1. Site general aspects

The hydroelectric power plant studied in this paper is an impoundment type and is located at 829 meters above sea level, with an average annual water temperature of 20 ºC. Its dam reservoir can store water until 63 meters height and is provided with a service spillway-auxiliary spillway combination.

The service spillway has vertical-lift gates used for normal operation and during extreme floods.

The auxiliary spillway was designed to divert flood water into an adjacent valley mainly for irrigation and environmental purposes, regulating water flow according to demand (FUGRO, 2014).

2.2. Auxiliary spillway system

The auxiliary spillway basically consists of a steel pipeline with 800 mm internal diameter and an approximated total length of 373 m, corresponding to a vertical section of 23 m fixed at the dam structure and the remaining pipeline section laid on a 350 m horizontal canal of 5 meters diameter. A Floodgate system formed by tandem butterfly-valves is located within the horizontal section and is accessible through this canal.

Auxiliary spillway intake is submerged and located at 40 meters below reservoir water level. There is a concreate grid house and a metallic grid over the pipeline intake to avoid debris which could be expected to flow through the auxiliary spillway, damaging the floodgates and the pipeline itself (FUGRO, 2014).

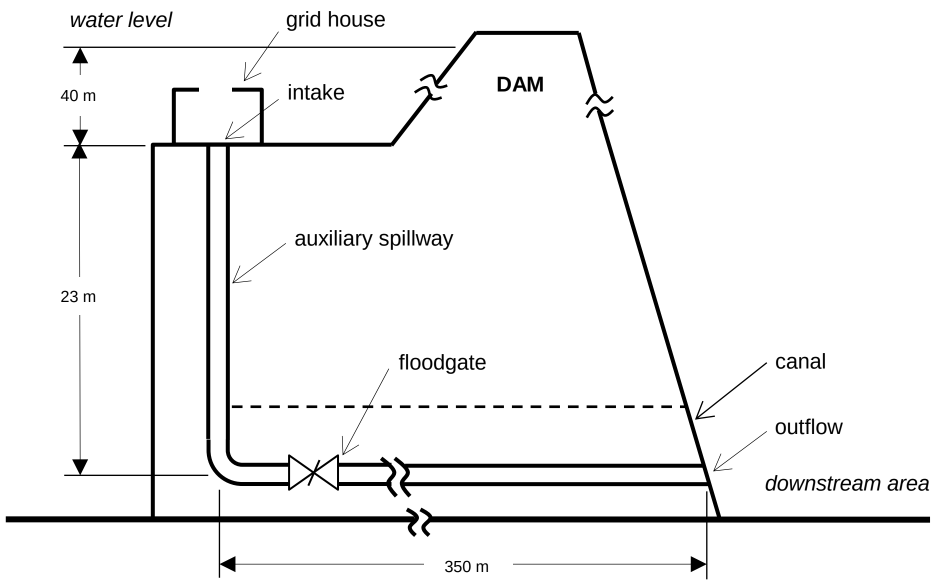


Figure 1. Auxiliary spillway system main parts

3. EMERGENCY FLOODGATE EQUIPMENT

3.1. Basic considerations

The configuration adopted for the auxiliary spillway system is very vulnerable regarding foodgate system maintenance.

In case of foodgate uncontrolled flow regulation due to an accident or mechanical fail, the only way to interrupt water flow is providing a blockage at intake region, so that a safe access along the canal for the foodgate maintenance team will be assured.

Once the maintenance is concluded, the auxiliary spillway water flow should be carefully augmented to avoid cavitation damage, until its nominal flow is achieved.

Within this scenario is imperative the utilization of emergency floodgate equipment - EFE, designed to interrupt and regulate the inlet water flow. The authors have been working in the feasibility analysis of an EFE project, mainly the fluid dynamics conditions associated to the EFE installation and operation.

Manufacturing aspects and logistics needed to guide and install EFE from reservoir level to quote -40 m are not the focus of this paper. Some design parameters will be omitted to preserve proprietary information.

3.2. EFE system concept

The EFE consists of two main modules (Fig. 2).

The first module performs the flow blockage of the auxiliary spillway pipeline at the intake. It contains a steel cylinder body, a hydraulic actuated *A type* butterfly valve and a polymer to seal EFE and grid house concrete base interface. A special locking device provides positioning and anchorage of the EFE first module onto grid house upper part.

The second module regulates the EFE water flow. It has a steel structure and a manifold with four hydraulic actuated *B type* butterfly valves. The second module is flanged onto the first module upper part.

Each butterfly valve disc can rotate 90 degrees from closed to open position. Its angular position is controlled by a hydraulic actuator driven by a command signal generated at the Control Station located onshore.

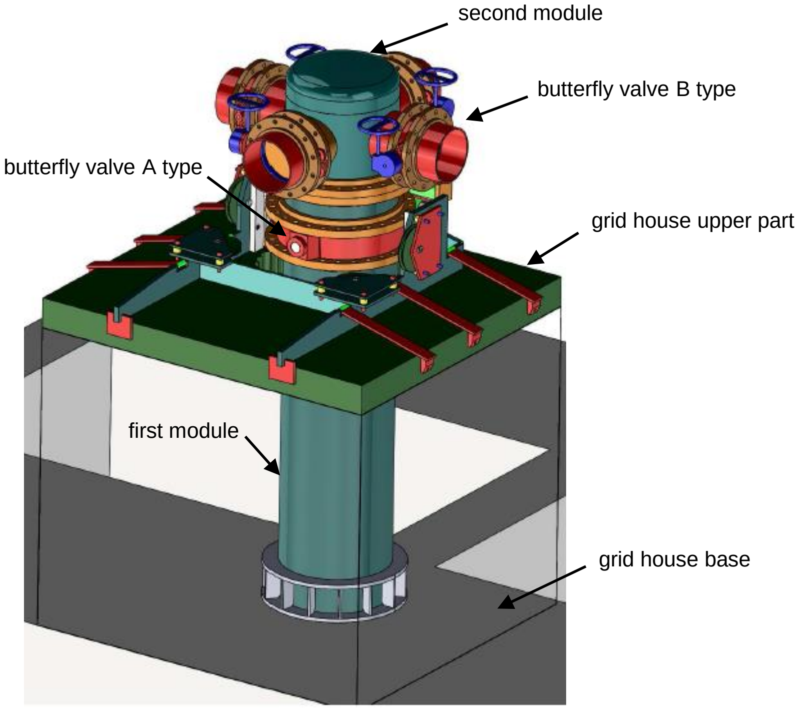


Figure 2. EFE system

3.3. Installation sequence

EFE complete installation sequence onto auxiliary spillway is described in Fig. 3 and Tab 1. The arrows indicate water flow qualitative behavior for each installation phase.

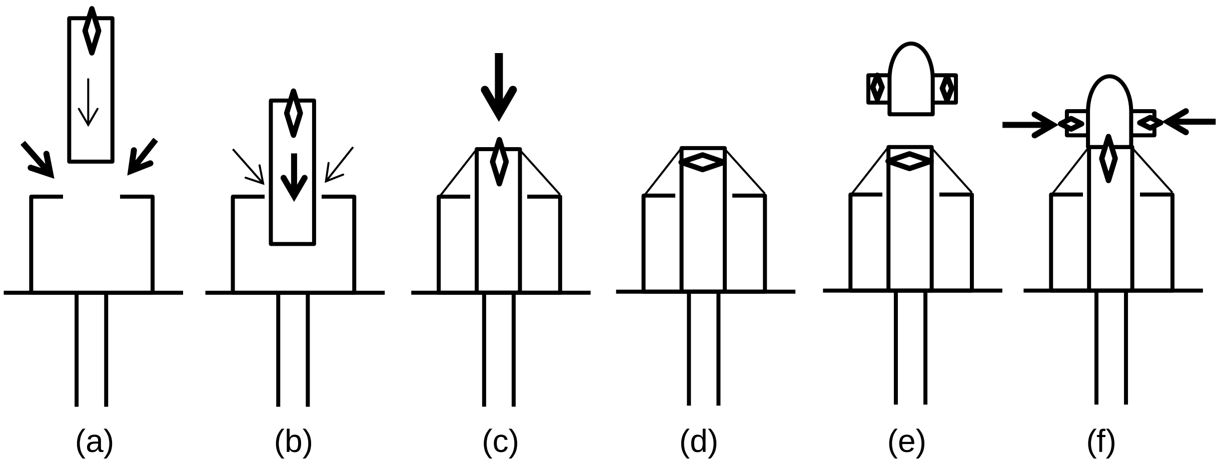


Figure 3. EFE installation sequence and water flow behavior

Table 1. Description of EFE installation sequence.

Phase	Description
(a) 1st module approach	Grid previously removed, 1st module concentric motion towards pipeline, opened valve, lateral and internal flows.
(b) intermediary	1st module concentric motion towards pipeline, opened valve, lateral and internal flows.
(c) installation at site	1st module positioned and anchored at grid house, opened valve, internal flow.
(d) flow blockage	closed valve, no flow.
(e) 2nd module approach	2nd module concentric motion towards 1st module, closed valves, no flows.
(f) flow regulation	2nd module flanged to 1st module, opened valves, flow regulation by 2nd module valves (B type).

3.4. EFE operation mode

The operation mode is associated to EFE water flow regulation, performed by four B type butterfly valves located at the manifold (namely A, B, C e D in Fig. 4), after the complete installation of 1st and 2nd modules onto the auxiliary spillway intake.

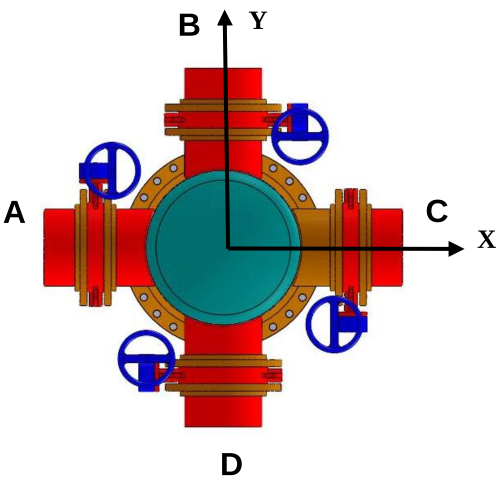


Figure 4. Superior view of the manifold

4. FLUID DYNAMICS NUMERICAL SIMULATIONS

4.1. Model considerations

4.1.1. Auxiliary spillway model

The fluid dynamics model of the auxiliary spillway needs to be obtained to adjust the existing operational conditions into the fluid dynamics behavior formulae related to EFE installation sequence and EFE regulation mode. The authors have used the available information concerning experimental and empirical data from the hydroelectric power plant operator, according to Tab. 2 (FUGRO, 2014).

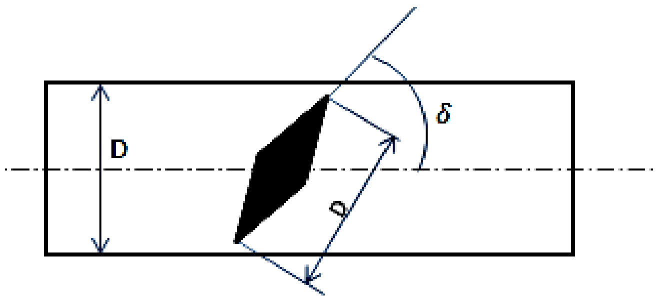
Table 2. Main available data for simulations.

Data Description	Values
Dam altitude from sea level	829 m
Dam reservoir height	63 m
Average annual water temperature	20^o
Estimated outlet water flow	4.6 m^3/s
Pipeline internal diameter	800 mm
Pipeline vertical to horizontal drag coefficient	k = 0.40
Outlet drag coefficient (opened orifice)	k = 0.60

Pipeline roughness	ε = 0.000045 m
Pipeline relative-roughness	ε/D = 0.000056

The floodgate system (butterfly valves) drag coefficient is associated to each valve opening disc angle, as presented in Fig. 5. This parameter was also given by the hydroelectric power plant operator.

The open disc configuration corresponds to δ = 5 degrees and a drag coefficient k = 0.24.



δ	K	δ	K
5°	0.24	40°	10.8
10°	0.52	45°	18.7
15°	0.9	50°	32.6
20°	1.54	55°	58.8
25°	2.51	60°	118.0
30°	3.91	65°	156.0
35°	6.22	70°	750.0

Figure 5. Butterfly valve drag coefficient (FUGRO, 2014)

4.1.2. General equations

The auxiliary spillway and EFE developed formulae are based on fundamental fluid dynamics equations (Faisabdier, *et al.*, 2006; Fox, *et al.*, 2014), such as:

$$\frac{P1}{\gamma} + \frac{{V_1}^2}{2g} = \frac{P2}{\gamma} + \frac{{V_2}^2}{2g} + \Delta H + \Delta Ht \quad \text{(energy conservation)} \tag{1}$$

$$\Delta H = f \frac{L}{D} \frac{V^2}{2g} \quad \text{(drag coefficient)} \tag{2}$$

$$\Delta Hl = K \frac{V^2}{2g} \quad \text{(local drag coefficient)} \tag{3}$$

$$\frac{1}{\sqrt{f}} = -2\, log10 \left[\frac{2.51}{Re\sqrt{f}} + \left(\frac{\varepsilon/D}{3,7} \right) \right] \quad \text{(Colebrook friction factor)} \tag{4}$$

The transcendental equations obtained from auxiliary spillway and EFE developed formulae were solved by numerical methods from the computational program Mathematica 7© (Wolfram, 2012).

The calculated parameters obtained for auxiliary spillway formulae with no butterfly valve are indicated in Tab. 3.

Table 3. Calculated parameters.

Data description	Values
Mean velocity	9.2 m/s
Reynolds number	Re = 7309591
Friction factor	f = 0.0113

4.2. First module installation phase

The fluid effects are most important in the flow through the intake region (Fig. 1) therefore, the flow analysis will be made in that region. Great part of the pressure loss (drag effects) happens in that (intake) region, where enormous unsteady hydrodynamic forces are generated.

The mean flow velocity, calculated using the flow rate is V_{ring}= 9.73m/s

The weight of the 1st module, P_{mod1}, was obtained using the CAD model considering the geometry and materials used.

Table 4. Calculated parameters for first module installation.

Parameter	Values
Mean velocity	9.37 m/s
Flange and pipeline (ring projected area)	F_{ring} = -16325 N
Butterfly valve	F_{valv} = -337 N
Internal and external walls	Fp = -1978 N
Total hydrodinamic forces	Fhid = -18640 N
First module weight	P_{mod1} = -14896 N
Buoyancy forces	F_{buoy} = 1960 N
Resultant forces on 1st module	**F_{1stmod} = -31577 N**

In order to avoid the instability of the 1st module structure during the descending procedure (Fig. 3b) and the consequent missing of the concentric configuration, a stabilizing lateral force due to the hydrodynamic pressure should be applied to EFE 1st module by the locking/positioning device, so that EFE 1st module and grid house upper part do not contact.

The pressure p is given approximately by:

$$p \approx \rho\, V_{ring}^{2}/2 \qquad (5)$$
$$p \approx 33374 \text{ Pa},$$

The lateral force can be calculated as:

$$F_{lat} = p.\, A_{proj} \qquad (6)$$

where
A_{proj} is the projected contact area between EFE structure and grid house upper part.

Then,
F_{lat} = 6007.4 N

4.3. Flow blockage

When the butterfly valve disc begins to rotate toward the closed position, it is subject to both the lift and drag forces of the flow stream (Flores, 2006; Kimura, *et al.*, 1995; Kitio and Nataraj, 2012; Norris, 2014; Wan, *et al.*, 2010).

It is assumed that the main force on the valve disc is due to the axial drag force. The radial force can be obtained from an extrapolation of the axial force. In Fig. 6 is presented the hydraulic forces generated at EFE butterfly A type valve during disc angle variation.

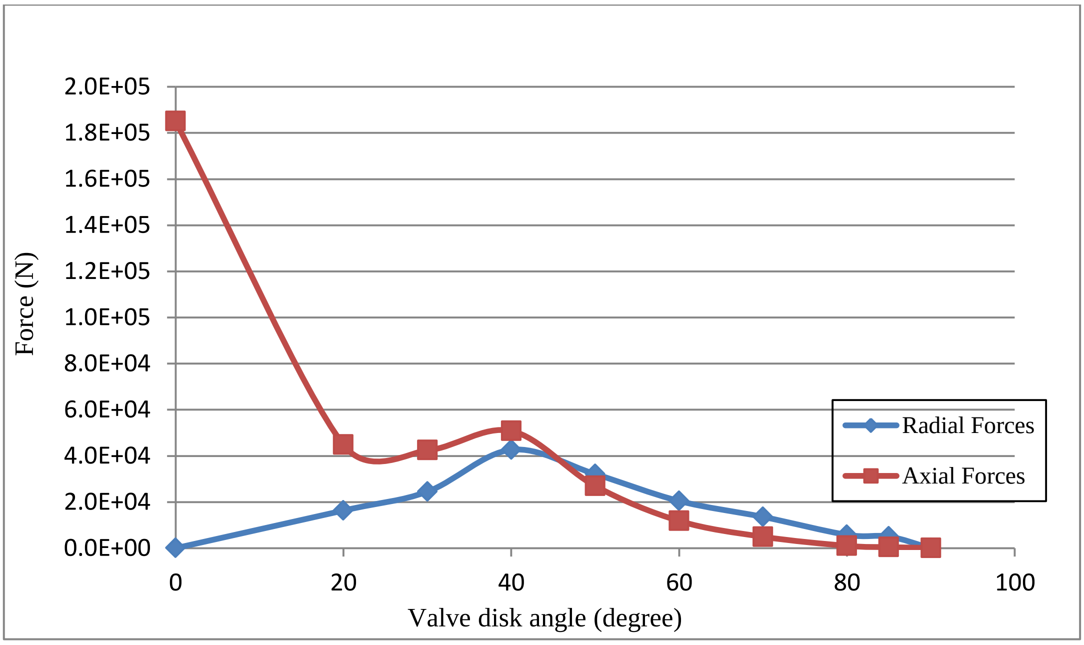


Figure 6. Forces at butterfly A type valve during disc angle variation

In Fig. 7, the values of the fluid pressures above the vaporizing pressure after the setting up of the butterfly valve are shown for various values of the valve disk angle. The blue line represents the flow pressure just after the butterfly valve and the black line the flow pressure on the pipeline entrance region.

It is clear that cavitation will be present and it occurs first at the pipe entrance region as expected. The negative values are just illustrative since the theory cannot predict that region.

Figure 8 presents the flow rate at EFE butterfly A type valve during disc angle variation.

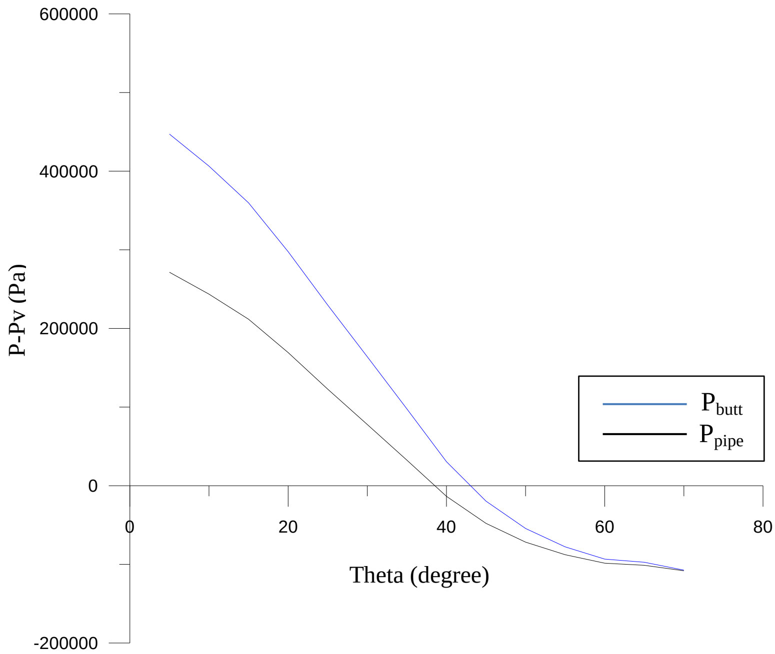


Figure 7. Values of the flow pressure above the vaporizing pressure on the butterfly valve (Theta=90^0- δ)

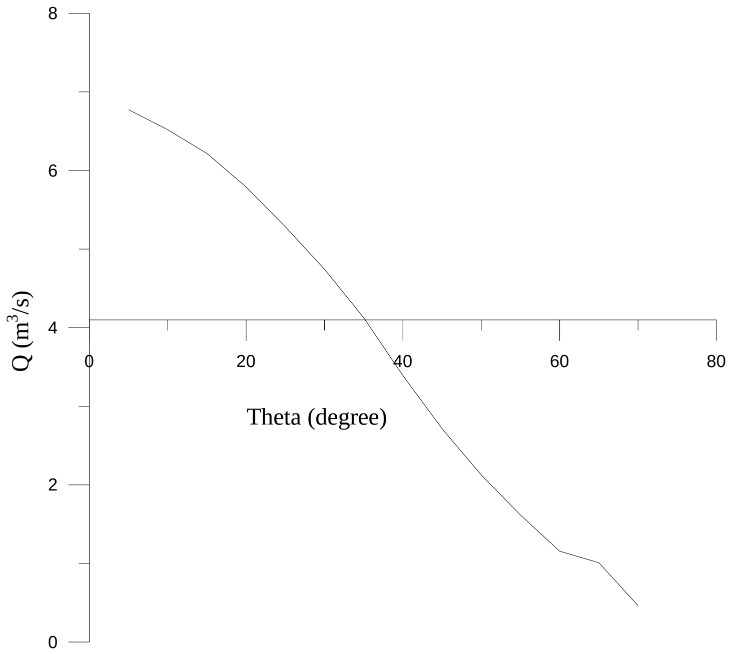


Figure 8. Flow rate.

5. CONCLUSION

Assuming a slow and controlled descendent procedure of the EFE 1st module concentric motion towards pipeline, the vertical acceleration and consequently the dynamical model of the structure can be neglected. Therefore, a resulting force of 32000N must be considered for the dimensioning of EFE motion/positioning equipment, so that its hydraulic cylinders can supply the necessary mechanical power to proceed EFE installation.

The model was developed assuming some conservative hypothesis and, because of that, the obtained values are presumed to be over the expected values.

The worst case scenario considering the hydrodynamic forces, is described in Fig. 3, where the velocities are very high. That situation was considered for the calculation of the forces on the structure and on the valve.

It was demonstrated that for a butterfly valve disk angle (theta) at about 40 degrees (see Fig. 6) the cavitation process starts to appear. This indicates that in order to avoid damages, essentially caused by the cavitation itself or by the strong unsteady forces associated with the flow, an angle of 40 degrees for the valve disk represents the maximum operational limit of the valve in the present situation after the complete blockage.

6. ACKNOWLEDGEMENTS

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