Hydraulic circuit description of the MGR Wave Energy Converter

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Abstract

This paper presents the hydraulic circuit of a new wave energy converter (WEC) design, the MGR. The MGR, due to its working principle, is a hydraulic circuit indeed. The MGR is a near shore submerged converter that takes advantage of the oscillating water column created by the wave when it passes on the converter's platform. The wave column pushes the platform, transmitting the force to a single acting cylinder, that pumps sea water to the coast, where is turbined generating electricity.

The study comprises the components definition and the pressure drop in the circuit. The filtered sea water taken from seabed is conduced to the single acting cylinder by a 3-way valve, where it is pumped to the accumulators. The accumulators store pressure energy, to damp cylinder pulses and assure a constant flow. The flow of different modules are collected and sent to the coast through an submerged pipe, where is transformed in electrical energy by a Pelton turbine.

Keywords:, hydraulic circuit, pressure drop, resonance with waves, submerged pipe, wave energy

Nomenclature

Re	=	dimensionless number
Cv	=	Hydraulic component pass factor
d	=	Depth (m)
d_c	=	Cylinder stroke (m)
D	=	Diameter (m)
ΔE	=	Energy loss ratio (m/m, %)
g	=	Gravity (9,81m/s^2)
h_f	=	Pressure drop (m)
L	=	Pipe length (m)
P	=	Pressure (m)
Q	=	Flow (m^3/s)
T	=	Wave crossing period (s)
v	=	Velocity (m/s)
z, Δz	=	Height, height difference between the converter and the turbine (m)
ε	=	Inner rugosity of the hose
γ	=	Kinematic viscosity
ρ	=	Density (kg/m^3)
η	=	Efficiency

Subscripts

c	=	cylinder
e	=	component
min	=	minimum
max	=	maximum
p	=	pipeline
t	=	turbine
z	=	height

1 Introduction

The presented study is part of an initial design approach of a new concept of Wave Energy Converter (WEC), the MGR. The proposed WEC is a small-medium power facility that uses well-known and reliable technologies, as Pelton turbine, synchronous generator and hydraulic components.

The MGR is classified as near shore submerged device [1]. The converter is placed on the seabed (7 – 8m depth) and 50 – 100m offshore. Its working principle bases on the oscillating water column created by the waves when they pass over the submerged platform. The platform pushes a single-act cylinder that pumps high pressure sea water to the coast by a pipe. The cylinder works against the pressure of the accumulators, which store energy, damping flow irregularities. This high pressure water impulses the turbine generating electricity.

The working principle, submerged and profiting oscillating water column, is similar to AWS and CETO I. The innovation is that the converter works in vacuum using springs to recover the original position, the

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variable working pressure and the fixed displacement of the platform. Instead massive energy production big power facilities, the MGR is thought for stand alone settlements, or connected to the grid. The nominal power output can be fit connecting different modules in parallel placed in linear array.

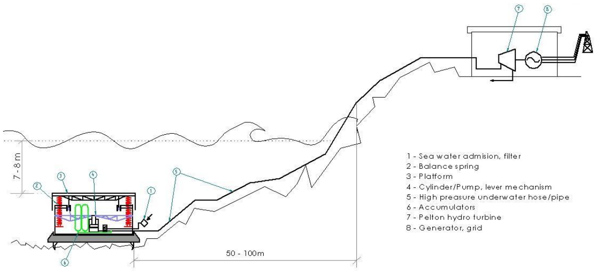


Figure 1: Proposed WEC diagram

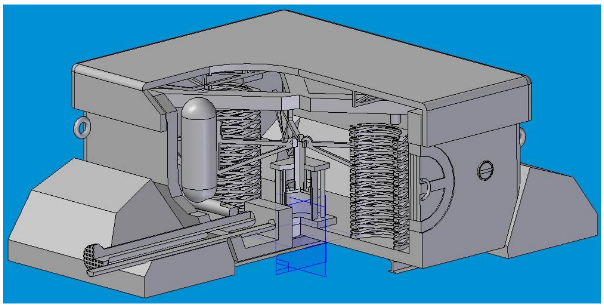


Figure 2: 3D CAD model of a MGR module

The control strategy is based on a variable working pressure and generator's load control. The energy absorbed by the WEC is maximum when platform's movement is tuned to the incident wave frequency [2]. Resonance is then said to occur. To achieve resonance condition,

- system pressure must create the appropriate resistance in the cylinder to match the coming wave's energy. System pressure is varied acting on turbine jet aperture, according to the wave size signal sent by the measuring buoy
- the output power is estimated according to the working pressure and the flow. The synchronous generator load torque signal is set according to the estimated power and turbine's optimal rotation speed (that depends only on system pressure)

In other words, the measuring buoy's wave size data (H, T) is used to foresee the optimal system pressure. If the pressure is bigger than the adequate, the piston cannot reach to cylinder bottom, and if it is smaller, not all the available wave energy is absorbed. On the other hand, to get the maximum efficiency, the turbine must work in its optimal rotation speed, that relates the pressure and generator's load.

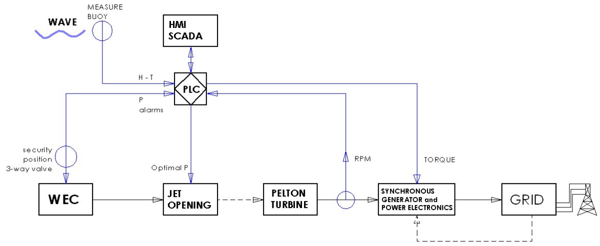


Figure 3: Control schema of the system

3. Circuit description

The MGR uses pressurised sea water as an intermediate medium to transform wave energy into electrical energy. Therefore it is very important to design carefully the hydraulic circuit in order to optimise the energy output. The materials used in the circuit must withstand the corrosive environment conditions produced by sea water. In addition, the components should create the smallest pressure drop to maximise the power-plant efficiency. The hydraulic circuit schema is shown in Fig. 4, while Table 1 presents the main components and describes their function,

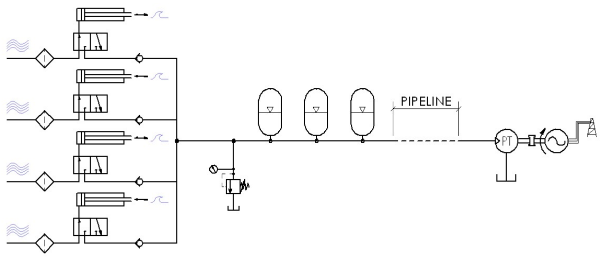
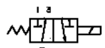


Figure 4: Hydraulic circuit schema

Component	Description
Filters	- water admission of the circuit - one per module - it has to filter the bulk of suspension substances from sea water (like sand, seaweed), and - it should create the minimum pressure drop to assure cylinder complete filling without cavitation
3-way valve  	- distribute the flow between the sea, cylinder and the circuit; - one per device; - electrical drive; - it works in on-off position only (not proportional), and - it should create the smallest pressure drop, that affects admission and circuit as well
Hydraulic Cylinder	- pump sea water, - one per device; - single acting cylinder - maximum working pressure 50 bar; - mounting configuration: fastened in the cap (bottom) - it is convenient to lighten as much as possible the moving parts, therefore the following changes are proposed: > hollow rod (tube or machined)

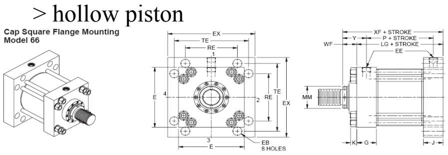
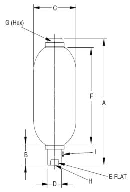
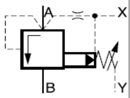
	> hollow piston 
Check valve 	- to avoid return flow to the cylinder, - one per device; - preference on ball, poppet check valves used in hydraulics than swing or ward valves used in water installations, because of the lower leakage and reliability - high flow capacity, low pressure drop - good contamination and corrosion resistance - flow range 40 – 20 l/s
Accumula-tors 	- for energy storage, - bladder type accumulators, three per device; - piston pump pulsation dampening and smooth wave height/period variance; - calibrated in different pressure levels, to work in adequate conditions at any pressure range - good contamination and corrosion resistance - working pressure range 25 – 44 bar NOTE: The bladder pressure should be located about 5% under working pressure, so the accumulator will supply extra flow to the circuit
Relief valve 	- to avoid over-pressures in the circuit in case of transitory pressure states to protect the circuit in normal operation, - one unit per facility - electrically piloted by the PLC - command pressure adapted for the optimal pressure in real time, so the turbine is not affected by sudden changes - good contamination and corrosion resistance
High pressure hose	- high pressure hose - withstand sea environment submerged - withstand abrasion in the inner hose - maximum working pressure: 50 bar

Table 1: Description of the hydraulic components

3 Hydraulic losses

Once circuit schema is defined (except pipeline diameter), the pressure drop produced in the circuit is estimated. There are three types of losses [3],

- pressure losses due the height difference between the platform and the turbine jet, $h_{fz} = f(z)$
- pressure drop in the pipeline, $h_{fp} = f(Q_P, D_P, L, \varepsilon)$
- energy losses caused by conduction elements, $h_{pe} = f(Q, D, Cv_i)$ where Cv_i is the pass factor of each element

In the following sections each loss type is studied separately. The study has been applied on a given disposition, where,

- cylinder diameter Dc = 500mm
- cylinder stroke dc = 550mm
- 4 modules in parallel
- minimum wave height- period 2m–6s
- minimum flow $Q_{min} = 0{,}4 m/s^3$ (T = 11s)
- maximum flow $Q_{min} = 0{,}7 m/s^3$ (T = 6s)
- minimum system pressure P_{min} = 25bar
- maximum system pressure P_{max} = 33bar

The hydraulic circuit study can be applied on different dispositions following the same steps taken in this study, adapting to the desired location.

4 Height difference

This loss is due to the difficulty in locating the turbine entrance at the converter's level or lower. This drifts onto static pressure drop (but not energy loss), defined as the height difference. It is highly recommended to minimise this difference. There is a limit for the elevation of the turbine, fixed by the highest spring tides adding the effect of the wind setup, wave setup and barometric pressure drop.

The dimensions of a possible configuration are shown in Fig. 5,

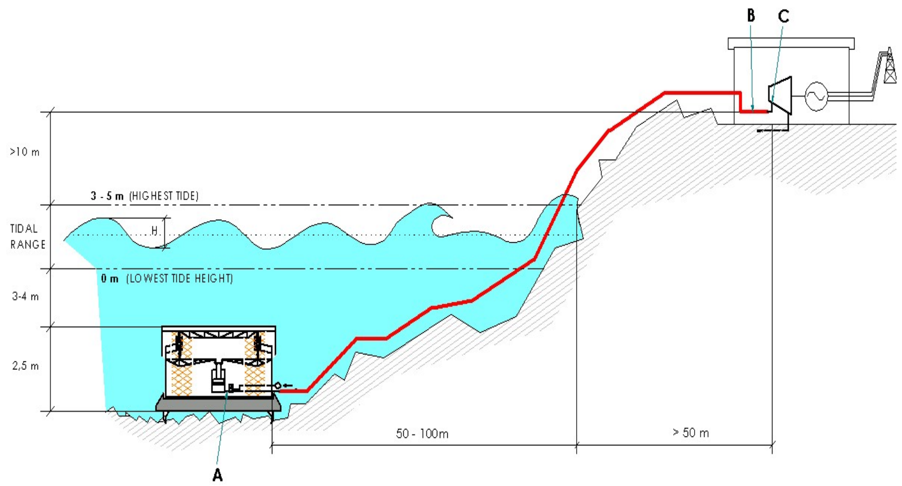


Figure 5: The MGR location depth and distance to the coast ranges, including the disposition of the pipe (in red); the figure locates the points where Bernoulli energy balance is applied (A, B and C)

Depending on the coast characteristics, this layout (length and height difference) will be adapted, changing the performance of the installation. The range of values that define the pipeline can vary between these ranges,

- Height difference $\Delta z = 16 - 22$m
- Pipeline length $L_p = 80$ -160m

To quantify the influence, applying Bernoulli equation (energy conservation) in points *A*, *B* and *C* (see Fig. 5), where *A* is the accumulator, *B* upper pipe and *C* turbine jet,

$$B_A - h_f = B_B = B_C$$

$$\frac{P_A}{\gamma} - h_f = \Delta z + \frac{P_B}{\gamma} + \frac{v_B^2}{2g} = \frac{v_C^2}{2g} \qquad (1)$$

The *Δz* term represents the height difference in (m), between the exit of the cylinder and the entrance of the turbine (it has not influence if the pipeline is located higher at certain point than turbine jet, syphon). 'P_i' is the relative pressure in the corresponding point in (m). The sum of *Δz* and P_i/γ represent the static energy component of the fluid. And v_i is the speed of the water in (m/s), the kinetic energy component. Studying this height difference, obviously the loss seems linear.

Δz (m)	15	16	17	18	19	20	21	22	23	24	25
$\Delta E_{z\text{-}220}$	6,82	7,27	7,73	8,18	8,64	9,09	9,55	10	10,4	10,9	11,3
$\Delta E_{z\text{-}310}$	4,84	5,16	5,48	5,81	6,13	6,45	6,77	7,1	7,4	7,7	8,06

Table 2: Height difference – system pressure ratio (in %) according to the minimum (220m) and maximum (310m) system pressure

The table shows that the loss ratio (%) is bigger at low pressures, because the loss is constant under any system pressure or flow rate. The turbine height must be as low as possible, even digging underground or protecting it from the waves with a wall.

5 Pipeline flow loss

Now it is the turn of the losses due the flow of water through pipe, the h_f term in Bernoulli's equation (1). This loss is a function of the pipe inner rugosity *ε*, hose length *L* and inner diameter *D*, and the square of water speed through the pipe *v* (related with flow and pipe diameter) [4]. The pressure drop can be calculated through Darcy-Weissbach equation,

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \qquad (2)$$

where the coefficient *f* is the friction factor, which can be obtained from Moody's chart, depending on the Reynolds number *Re*, pipe inner rugosity *ε*, flow and pipe diameter. Applying on the given pipe,

- The design friction factor *f* for a Pelton turbine conduction is 0,012 – 0,015
- The average rugosity *ε* for PVC/PE tubes is 0,0007 (reinforced high pressure hoses)
- The Reynolds number *Re* is the ratio of inertial losses to viscous forces for a given flow condition; it is dimensionless

$$Re = \frac{vD}{\gamma} \qquad (3)$$

- The speed in the pipe depends on the flow and diameter

$$v = \frac{4Q}{\pi D^2} \qquad (4)$$

- The smooth pipe zone limit *Re'* (see Moody's chart, Fig. 6) is calculated as follows,

$$Re = \frac{23}{\epsilon / D} \qquad (5)$$

- Moody´s chart leads the friction factor f, entering with Reynolds number *Re* and the relative rugosity *ε/D* (see Fig. 6)

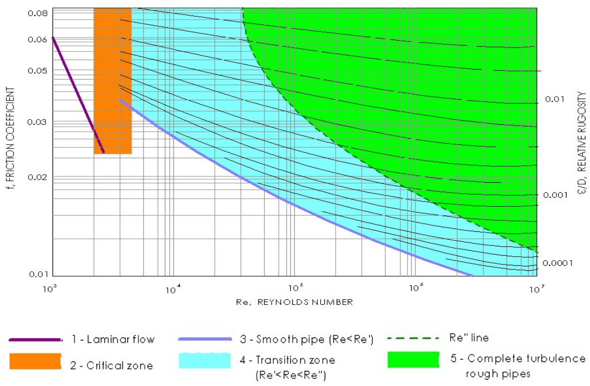


Figure 6: Moody friction factor diagram divided in different areas depending of the flow type and interaction with pipe surface

$Re < 2000$ laminar flow
$2000 < Re < 4000$ indeterminate flow
$Re > 4000$ turbulent flow

A compromise must be found between a reasonable diameter and an acceptable pressure drop. The loss is function of the square speed of water; the friction factor depends on square speed too, and the speed on the flow and diameter.

D mm	ε/D	v_{1MAX} m/s	v_{1MIN} m/s	Re_{1MAX} -	Re_{1MIN} -	f_{1MAX} -	f_{1MIN} -	h_{f1MAX} m	h_{f1MIN} m
50	*0,00014*	35,65	20,37	1,5,E+06	8,5,E+05	0,014	0,0142	**2720,7**	**901,1**
60	*0,000117*	24,76	14,15	1,2,E+06	7,1,E+05	0,0135	0,0141	**1054,3**	**359,5**
70	*0,00010*	18,19	10,39	1,1,E+06	6,1,E+05	0,0133	0,0141	**480,5**	**166,3**
80	*0,000088*	13,93	7,96	9,3,E+05	5,3,E+05	0,0132	0,014	**244,6**	**84,7**
100	*0,00007*	8,91	5,09	7,4,E+05	4,2,E+05	0,0134	0,0144	**81,37**	**28,5**
125	*0,000056*	5,70	3,26	5,9,E+05	3,4,E+05	0,0136	0,0147	**27,06**	**9,55**
150	*0,000047*	3,96	2,26	5,0,E+05	2,8,E+05	0,0138	0,0153	**11,03**	**3,99**
175	*0,00004*	2,91	1,66	4,2,E+05	2,4,E+05	0,0144	0,016	**5,33**	**1,93**
200	*0,000035*	2,23	1,27	3,7,E+05	2,1,E+05	0,015	0,0165	**2,847**	**1,02**
250	*0,000028*	1,43	0,81	3,0,E+05	1,7,E+05	0,0153	0,017	**0,951**	**0,345**
300	*0,000023*	0,99	0,57	2,5,E+05	1,4,E+05	0,016	0,0177	**0,400**	**0,144**
350	*0,00002*	0,73	0,42	2,1,E+05	1,2,E+05	0,0164	0,0183	**0,190**	**0,069**
400	*0,000017*	0,56	0,32	1,9,E+05	1,1,E+05	0,0167	0,0188	**0,099**	**0,036**

450	***0,000016***	0,44	0,25	1,7,E+05	9,4,E+04	0,017	0,0193	**0,056**	**0,021**
500	***0,000014***	0,36	0,20	1,5,E+05	8,5,E+04	0,0175	0,0199	**0,034**	**0,013**

Smooth pipes line (3th stage), Re < Re'

Table 3: Pipeline losses according to hose diameter and high-low flow rates

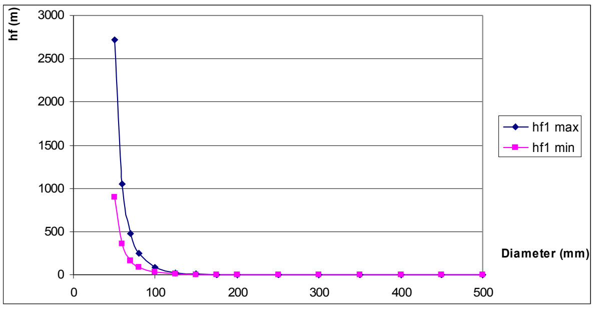


Figure 7: Pipeline losses, representation of the results achieved in the Table 3 (losses over 300m are not showed)

In Table 3 the losses for each standard commercial diameter are shown, for both, highest and lowest flow. The pipe length has been set 150m for comparison.

Both show that losses begin to be close to zero using diameters over 175 mm. That is the reason to choose 175mm hose for this configuration.

When the diameter is fixed, the influence of the length seems to be linear based on Darcy-Weissbach equation (2). the next table shows the losses for different lengths and flows for a given diameter, 175mm.

Q m^3/s	f	h_f/m m/m	PIPELINE LENGTH (m)						$\Delta E_{e\text{-}220}$	$\Delta E_{e\text{-}310}$
			80	100	120	140	150	160		
0,07	0,0144	***0,0355***	2,84	3,55	4,26	4,97	5,33	5,68	*2,24 %*	*1,72 %*
0,06	0,0149	***0,0271***	2,17	2,71	3,25	3,79	4,06	4,33	*1,84 %*	*1,31 %*
0,05	0,0155	***0,0195***	1,56	1,95	2,34	2,73	2,92	3,11	*1,37 %*	*0,94 %*
0,04	0,0160	***0,0129***	1,03	1,29	1,55	1,80	1,93	2,06	*0,88 %*	*0,62 %*

Table 4: Pressure drop in the pipe depending on pipe length and flow, for 150mm pipe diameter. The table includes pressure drop – working pressure ratio for $\Delta E_{e\text{-}220}$ minimum flow and $\Delta E_{e\text{-}310}$ maximum flow

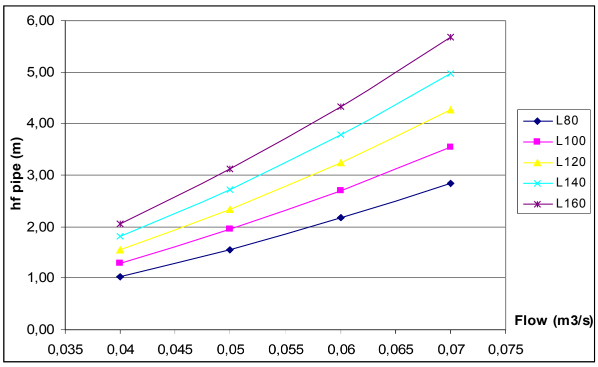


Figure 8: Losses depending on pipe length and flow. Representation of Table 4

Obviously, the losses increase linearly for the same length when the flow is increased, obtaining the lowest pressure drop with the lowest flow rate.

6 Losses in the circuit components. Pass factor method

The losses created by conduction components are estimated using the pass factor method. This method simplifies the calculus supposing the pressure drop on each component proportional to the square flow speed. The proportionality is defined by a constant, characteristic for each component, *Cv*. Actually, the pass factor is an important criterion to compare components of different manufacturers. Summing all coefficients, the result is the overall pressure drop created by hydraulic components. The pressure drop in (m) is defined as follows,

$$h_f^i = C_V \frac{v^2}{2g} \qquad h_f^e = \sum C_V \frac{v^2}{2g} \tag{6}$$

Here there are the hydraulic components listed. To estimate the pressure drop created by the components, the pass factor of the components chosen from the Parker commercial catalogue [5],

three-way valve*	Cv = 0,2	0,2
check valve*	Cv = 0,8	0,8
4 accumulators (T-intersection)*	Cv = 0,4 x 4	1,2
relief valve	Cv ≈ 0	0
10 -15 smooth bends, small angle	Cv = 0,08	1
4 T-intersections	Cv = 0,4 x4	1,2
2 progressive section changes	Cv ≈ 0	0
Estimated pass factor (*sum*)		**4,4**
Unexpected losses (security factor)	**x 1,7**	
TOTAL		**7,5**

The elements listed with an asterisk (*) are placed in each module, being their flow a fraction of the combined flow and working under the same pressure. Related with their nominal diameter, their speed is almost the same. Supposing that the pressure drop is the same in all of them, instead of summing them, it has to be counted only once, extrapolating to a drop caused by one component with the same pass factor, considering the total flow. Table 5 shows the pressure drop according to the flow for the given overall pass factor, knowing that the flow range is between 0,04 and 0,07m^3/s.

Q m^3/s	v m/s	h_f^{Cv} m	$\Delta E_{e\text{-}220}$	$\Delta E_{e\text{-}310}$
0,07	2,91	**3,19**	*1,45%*	*1,03%*
0,06	2,49	**2,35**	*1.07%*	*0,76%*
0,05	2,08	**1,63**	*0,45%*	*0,53%*
0,04	1,66	**1,04**	*0,47%*	*0,33%*

Table 5: Pressure drop due the flow through the components. Energy loss ratio calculated dividing the sum of drop by the highest/lowest system pressure ($\Delta E_{e\text{-}220}$, $\Delta E_{e\text{-}310}$)

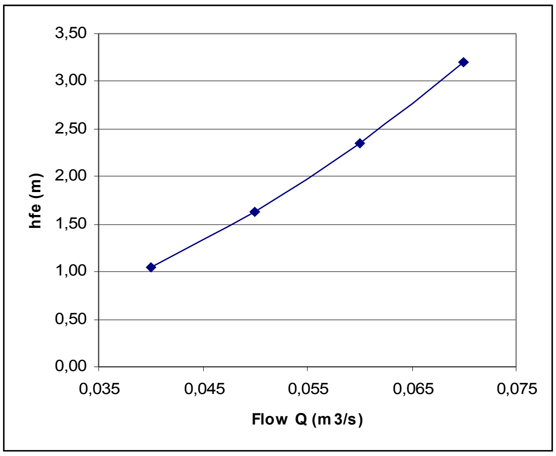


Figure 9: Pressure drop caused by the components according to the flow. Representation of Table 5

The graph seems slightly parabolic because of the square speed. The components total pressure drop represents the 1,5% at the highest flow and lowest pressure. The proportion deceases to 1% if systems pressure is the highest with the highest flow.

7. Total pressure drop in the circuit

Summing the three pressure drop types studied, the overall pressure loss created in the hydraulic circuit is,

$$h_f = h_{fz} + h_{fp} + C_V^t \cdot \frac{v_P^2}{2g} = \Delta z + \left(f \cdot \frac{L}{D} + C_V^t \right) \frac{v_P^2}{2g} \qquad (7)$$

8. Discussion and conclusions

The paper has presented the study of the hydraulic circuit for proposed MGR design. The aim of the study has been to determine the effect of the variable flow and pressure on the performance; and to set the design procedure to deploy the facility in a given location and conditions, to asses the feasibility. Beside these objectives, the pressure drop study has been implemented in the MGR´s control algorithm and simulation model in order to represent the process as complete as possible.

After describe the circuit, three pressure drop types have been defined: the height difference between the converter and the turbine, energy losses in the pipeline and pressure drop in hydraulic components. The following points have been concluded,

- the height difference between the converters and the turbine must be as low as possible,
- there is an optimal pipe diameter, where the pressure drop does not decrease as the diameter is increased
- the pressure drop in circuit components depends on the flow and components' pass factor; their selection is critical as it affects on the efficiency,

This study should be validated performing scaled prototype tests in wave tanks.

Acknowledgements

The development of the MGR would not be possible without Margarida Coelho's encouragement. The idea came up in Ordizia, during the weekly dinner with Jon Sagastizabal.

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