Diaphragm in pressure pipe: Steady state head loss evolution and transient phenomena

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Abstract: *With liberalization of European market, many high head power plants in Switzerland increase their potential generation to remain competitive. The existing surge tanks have to be modified to keep the flow management constant. A relevant way to limit the time of mass oscillation is to increase head losses at the entrance of a surge tank with an orifice. This study focuses on the influencing parameters of head losses at the entrance of an existing surge tank by a variation of geometry and position between this surge tank and the headrace tunnel. Then, the temporal evolution of head losses is evaluated under unsteady conditions during an emptying of the surge tank.*

Keywords: *Diaphragm, orifice, surge tank, transient, head loss*

1. INTRODUCTION

The electricity market is changing. The demand and electricity needs are still growing (Pannatier, 2010). This increasing is due to world demographic and improvement of social level in developing countries (Nicolet, 2007). The consumption is expected to double between 2003 and 2030 (Nicolet, 2007). Furthermore, the market liberalization is under way in Western and Central Europe (Jamasb & Pollitt, 2005). Historically, the production was composed of thermal plants (nuclear, coal, oil, gas, etc.) producing a constant amount of energy. Small thermal or hydraulic plant followed cyclic demand, such as daily, weekly or seasonal, to produce the peaks of demand. Since 90's, the part of renewable electricity has been increasing (Jamasb & Pollitt, 2005). The growing ratio of both solar and wind is close to 30% in OECD Europe (IEA, 2013). However, these renewable production of electricity is hardly controllable (Anagnostopoulos & Papantonis, 2008; Brown et al, 2008). In other words, the offer doesn't follow the demand and is only forecastable for a few days.
The hydropower has to fit new rules of the market to remain competitive. The competitiveness of a hydropower plant is a function of its ability to follow the peak-load demand and to produce large amount of electricity in a short time when there is a lack of production elsewhere (Schleiss 2007; Schleiss 2012). In this situation, many high head hydropower plants, whose head is higher than 200 m, are increasing their installed generation capacity. In many cases, this increasing of generation results in an increasing of flow discharge in the system. For a non-modified installation, a rise in flow leads to a growth of the time of the oscillation of mass. This phenomenon restrains a new starting during few minutes. An economical way to reduce this duration and extreme oscillations is to place an orifice, or throttle, at the entrance of the surge tank to increase local head losses.
The FMHL (Forces Motrices Hongrin-Léman) doubled their generation capacity. A previous study determined the geometry of a diaphragm(orifice) placed in the tunnel connecting a new surge tank and the existing headrace tunnel. The present study is focused on the evolution of head loss coefficient of a diaphragm's orifice by varying its position in the connecting tunnel. Then, the evolution of head losses when the surge tank empties is evaluated to represent the transient behaviour of head losses.

2. MATERIALS AND METHODS

2.1. Prototype and location

The FMHL is a pumped-storage power plant located in the Canton of Vaud in the south-west of Switzerland. The FMHL exploits the head between Reservoir Hongrin (1255 masl) and Lake Geneva (372 masl) (Figure 1). This pumped-storage power plant was commissioned in 1971. It had a power of 240 MW divided in 4 units and a total discharge of 33 m^3/s in generation and 24 m^3/s in pumping mode.

A new powerhouse is built and equipped with two units (Pelton turbine and multistage pumps) for a total capacity of 240 MW increasing the total potential power generation to 480 MW. The total discharge increases to 57 m^3/s in generation and 43 m^3/s in pumping. The existing installation (headrace tunnel, pressure shaft, etc.) is able to support this new load. However, a new surge tank will be built to ensure optimum safety in transient phenomena (Hachem et al., 2013) (Figure 2).

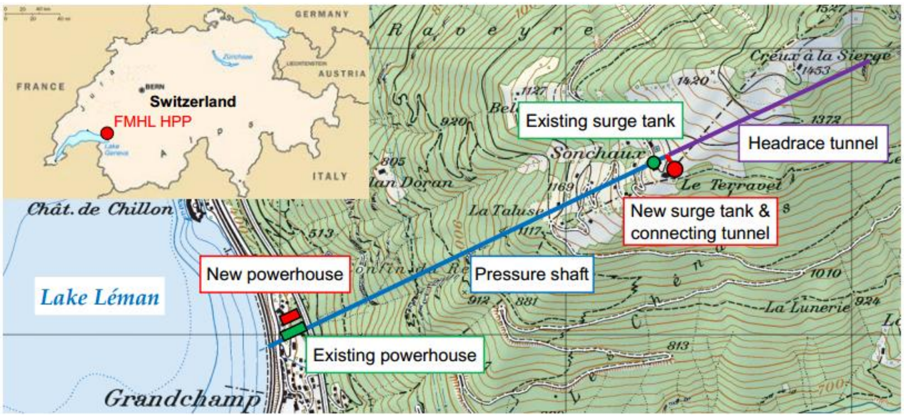


Figure 1 – Location of FMHL Pumped-storage plant and plan view of existing scheme and the new one (Hachem et al., 2013).

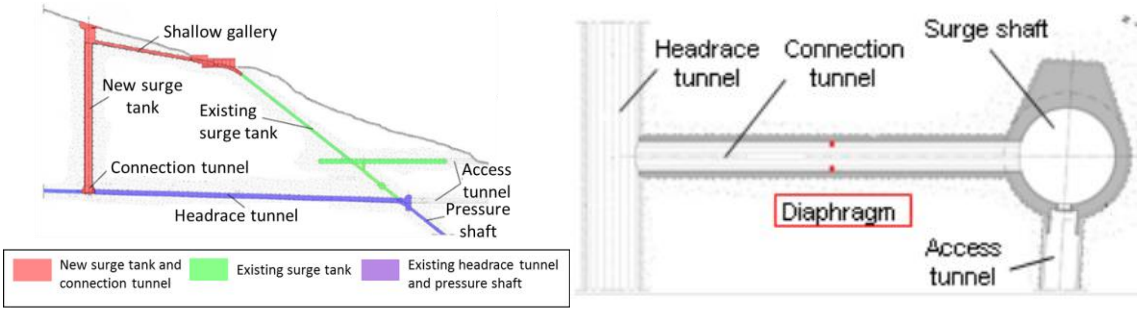


Figure 2 – (a) New vertical and existing surge tank (Hachem et al., 2013); (b) Plan view of the new (Hachem et al., 2013).

A previous study (Hachem et al., 2013) focused on the design of this new surge tank and a diaphragm's orifice in the connecting tunnel. This design relies on a 1-D numerical model testing the worst cases of transient phenomena (A closure of valve followed by an opening). To satisfy the target safety level, it has been decided to create head losses at the entrance of the new surge tank with a diaphragm's orifice. The chosen internal diameter, d, of the orifice is 1.63 m with a contraction ratio $\beta = \frac{d}{D}$ of 0.74. The Laboratory of Hydraulic Constructions, LCH, of École Polytecnique Fédérale de Lausanne EPFL carried out the determination of this geometry by physical modelling.

2.2. Experimental set-up

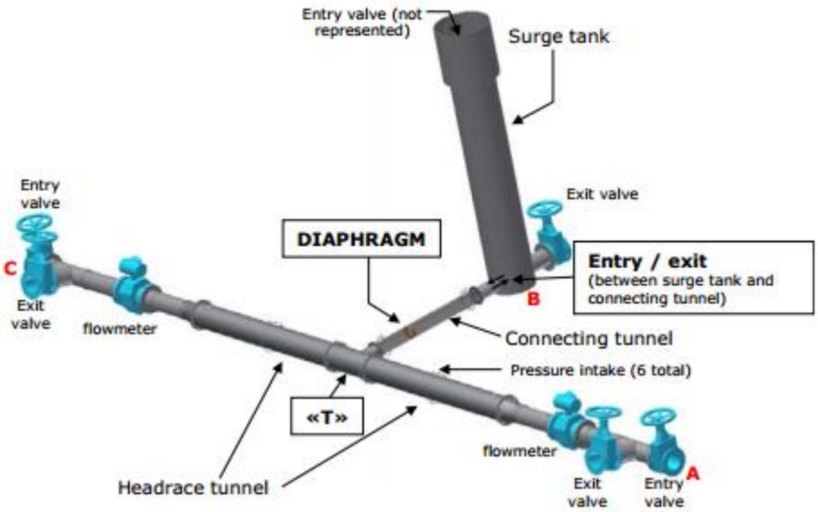
All the tests were performed on the model at LCH in a 1:18.2 scaled model using a Froude similarity, which respects the ratio between inertia, and gravity forces assuming the last are more important (Table 1). As shown in Figure 3, the model represents the new surge tank, the headrace tunnel and the connecting tunnel, which contains the diaphragm's orifice. This orifice can be displaced in the connecting tunnel. The four position are (in prototype scale): P_a, 7 m from the axis of the headrace tunnel, P_b, 13 m; P_c, 19 m and P_d, 24 m (Figure 3). Two internal orifice diameters are tested: the first has an opening of 1.55 m ($\beta = 0.7$) and a second has the project opening of 1.63 m (both in prototype scale).

Six measurement sections with 4 water outputs located around the conduit use piezoresistive pressure sensor (Keller – series 25) to evaluate the pressure in each section. These measurement section are allocated as follow: S_1 and S_2 in conduit A; S_3 and S_4 in conduit B; and S_5 and S_6 in conduit C. These sections are used to find the head loss coefficient.

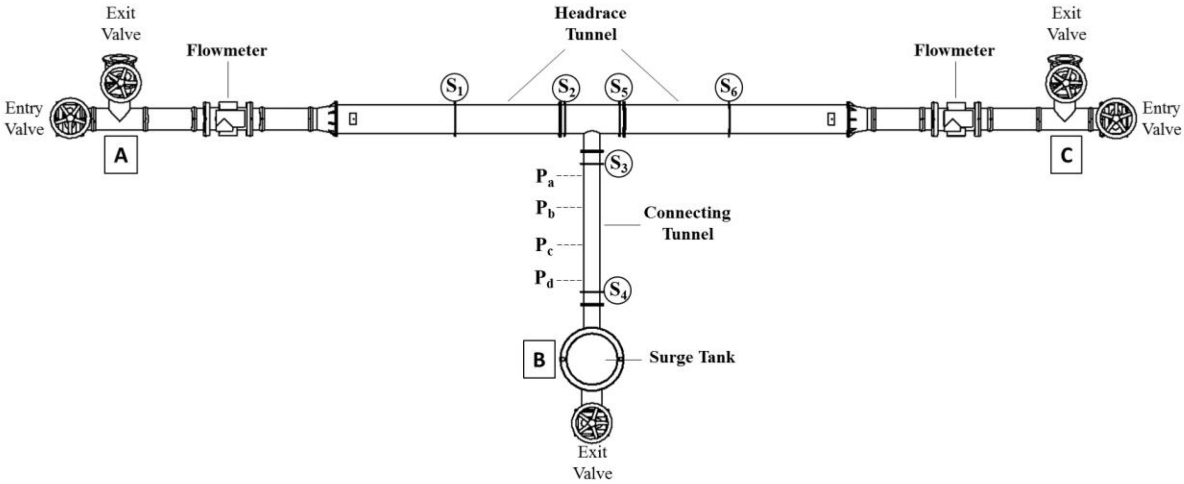
Two electromagnetic flowmeters (Endress-Hauser – PROMAG 50 W) are placed to record the discharge.

Table 1 Scale factors of the main physicals parameters

Physical parameters	Scale ratio	Scale factor
Length [m] Pressure [m]	λ	18.2
Velocity [ms^{-1}] Times [s]	$\lambda^{1/2}$	4.27
Discharge [m^3s^{-1}]	$\lambda^{5/2}$	1 413



(a)



(b)

Figure 3 – Schematic drawing of the model in the LCH: (a) 3D-view (Hachem et al., 2013); (b) Plan view + position of the diaphragm's orifice

2.3. Evaluation of steady head losses

Head losses in a turbulent flow are linearly proportional to the kinetic energy as shown in Eq. (1) (Blevins, 1984; Idelchik & Fried, 1986).

$$\Delta H = k\frac{v^2}{2g} \tag{1}$$

In this study, a set of 6 to 8 discharges is used to determine the head loss coefficient. To ensure a full turbulent flow and a high accuracy to determine the head loss coefficient, the smallest Reynolds number in the connecting tunnel is higher than 1×10^4 as recommended by Blevins (1984). The method of least squares is used to evaluate the head loss coefficient.

Hachem et al. (2013) concluded that the head loss coefficient is the same for both mean flow A – B and C – B, only directions C – B and B – C are carried out.

For each position P_i, the head loss coefficient is found by applying Bernouilli's law between the section S_6 and the surge tank, S_B. Eq. (2) and (3) show Bernouilli's equation for both directions C – B and B – C for an incompressible flow with neglecting friction produced by viscous forces. Note that a uniform velocity profile is assumed without correction factor and that a hydrostatic pressure distribution is also assumed.

$$\Delta H_{6-B} = (Z_6 - Z_B) + \frac{(p_6 - p_B)}{\rho g} + \frac{(v_6^2 - v_B^2)}{2g} \tag{2}$$

$$\Delta H_{B-6} = (Z_B - Z_6) + \frac{(p_B - p_6)}{\rho g} + \frac{(v_B^2 - v_6^2)}{2g} \tag{3}$$

Where: Z_i is the altitude of point i; p_i the pressure and v_i the flow speed.

The pressure sensors S_i recorded the mean piezometric head (altitude and pressure) from 1500 samples data acquired at a frequency of 100 Hz (the total duration of data acquisition is 15 seconds). In the same way, flow velocities are deduced from the flow meter with the same recording parameters. The head loss cross-section is defined as the cross-section of connecting tunnel.

2.4. Transient experiments

Currently, in practical hydraulic, the transient head losses are considered the same as in a steady flow (Chaudry, 1979). Experiment was carried out by opening as quickly as possible the exit valve C with a full surge tank B. The emptying of the tank takes approximately 20 seconds. The recording begins few seconds before and ends 10 seconds with a frequency of 100 Hz. Only the transient behaviour is shown.
Each 0.01 seconds, the head losses and head loss coefficient are determined instantaneously. These unsteady head losses are compared to the steady head loss coefficient.

It is important to note that as the evaluation of head losses is instantaneously evaluated, resulting errors are greater than in the steady state. Eq. (3) is used as the water is flowing from the surge tank.

3. RESULTS

3.1. Steady head losses

Both orifices are tested in all four positions. Figure 4 shows head losses as a function of kinetic energy for both internal diameters for the direction B – C. For all head loss coefficients, the coefficient of determination is always higher than 0.99 confirming the theoretical definition of the head losses shown in Eq. (1). Furthermore, Figure 4 shows that the smaller the internal diameter is, the higher the head losses is.

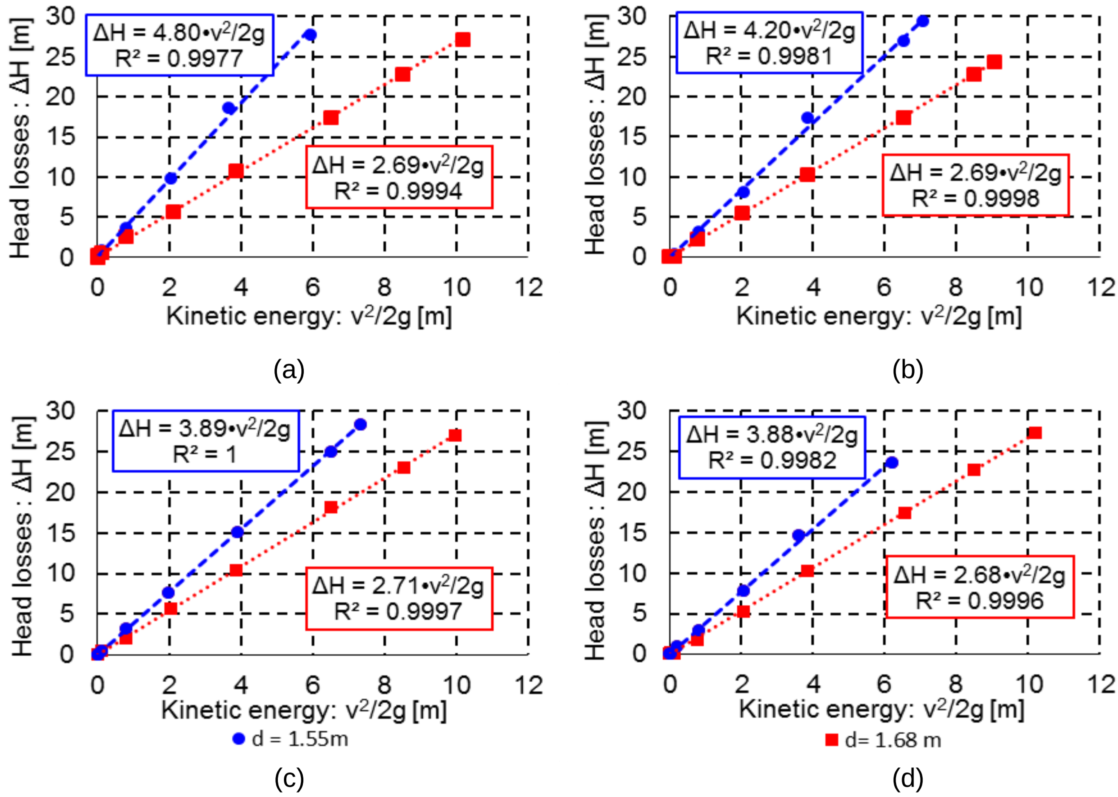


Figure 4 – Evaluation of steady head losses for the direction B – C: (a) Position a, P_a ; (b) P_b ; (c) P_c ; and (d) P_d (Results are shown in prototype scale)

Figure 5 represents the evolution of the head loss coefficient as a function of the position of the orifice for both internal diameters. The position in the connecting tunnel doesn't seem to have any influence on head losses for the biggest internal diameter. On the other hand, this variation of position has an effect on head losses generated by the smallest internal diameter for the positions close to the T-junction.

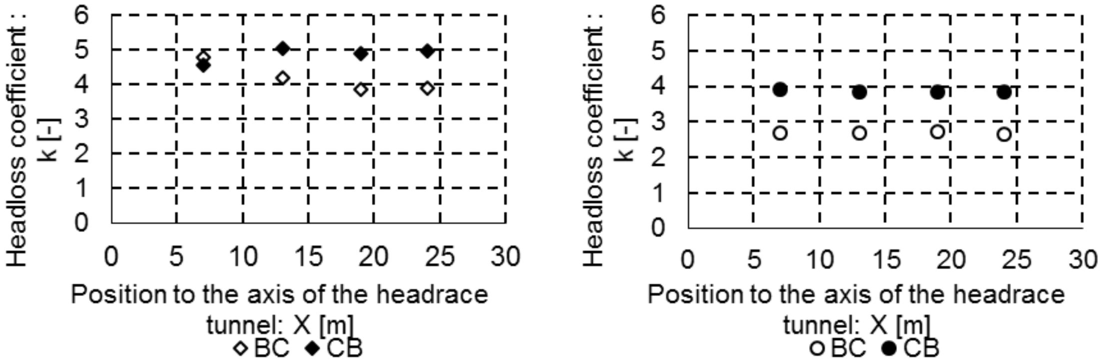


Figure 5 – Evolution of steady head losses as a function of the position in the connecting tunnel ($X = 0$ is the axis of the headrace tunnel) in both directions: (a) internal diameter of 1.55 m; (b) 1.69 m (Prototype scale).

From Figure 5, the head losses for both orifices can be compared to standard hydraulic engineering books (Blevins, 1984). These standard values are higher than the experimental head loss coefficients. For example, for the smaller internal orifice, the standard value is 4.7 and found values are 2.5 for B – C and 3.9 for B – C. As the head losses are measured previously without any diaphragm, the experimental values are evaluated by subtracting the head losses without diaphragm (Hachem et al, 2013). In this way, the influence of the T-junction is theoretically eliminated and only the orifice's head losses could be highlighted.

3.2. Transient experiments

The head loss coefficient between S_4 and S_6 is evaluated in the same way as explained in Section 2.3 for B – C direction. The value of this head loss coefficient is 3.2 for the position P_c. The test was carried out with duration 20 seconds.

The discharge flow and the head in S_4 and S_6 are reported in Figure 6. For the further analysis, two parts of the entire data set have been removed for the following reasons:

(i) For 0 – 10s: the recordings is influenced by the manually opening of the downstream valve.
(ii) From 30s: the difference of pressure between the two measured sections is smaller than the measurement precision (0.001 m at model scale).

The interesting part is for this example between the 10 and 30 s.

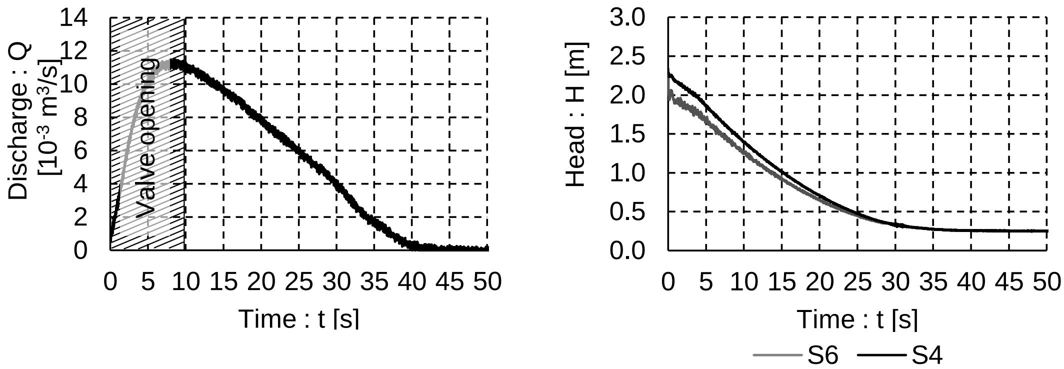


Figure 6 – Evolution of the discharge (a) and heads (b) as a function of time for the first transient experiment (Model scale).

Figure 7 shows the temporal evolution of the instantaneous head loss coefficient. During the first phase ($10-18s$) the head loss coefficient is quite similar to the steady head loss coefficient (4.5% less). For the second phase ($18-24s$), the head loss coefficient decreases quickly to remain stable (10.4% less). From the beginning of the last phase, the instantaneous head loss coefficient falls until the end of the experiments. This deviation becomes quite important from the moment where head losses are similar to the physical errors and data fluctuations become very large.

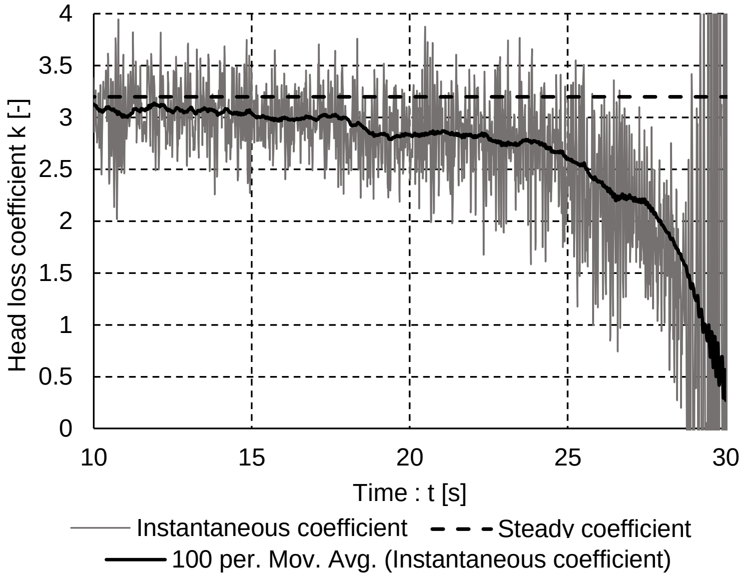


Figure 7 – Evolution of head loss coefficient in the studied area (Reynolds number varies from $1.13\cdot10^5$ to $3.6\cdot10^4$)

4. DISCUSSION

This study is focused on the head loss coefficient of a diaphragm's orifice and the behaviour on these head losses in steady and unsteady conditions between a surge tank and a headrace tunnel of an existing pumped-storage plant.

As expected, the internal diameter influences largely the head losses which increase when β decreases. However, the smaller internal diameter is subject to an interaction with the position in the connecting tunnel and, more precisely, the T-junction.

On one hand, when water flows from the surge tank, the head losses increase when the diaphragm's orifice is placed close to the T-junction. Jianhua et al. (2010) showed that as the length of recirculation length is higher when the internal diameter decreases. This can explain that the effect of position on head losses for the smaller orifice. With this orifice, the expansion occurs partially in the T-junction and causes a higher expansion and head losses. This can be confirmed as the head losses increase when the orifice goes from P_b to P_a.

On other hand, the upstream velocity field seem to have an influence on head loss coefficients. For the smaller diaphragm, the head loss coefficient decreases when it is close to the T junction and the velocity field are not yet established (Salvarli, 1980). Furthermore, for both orifices, the experiment values are smaller than the expected values (see Section 3.1).

For transient experiments, the tests show that instantaneous head losses are similar to the steady head losses evaluated over a data set of 1500 points. It can be observed that the instantaneous head loss coefficient decreases slightly in two steps. This drop becomes critical when head losses are of the same order of magnitude as the measurement errors. For a decrease of discharge, the head losses are always smaller than the steady head losses (for the four carried tests). It would be interesting to study the evolution of head losses with an increase of discharge.

5. CONCLUSION

This study has been performed with two distinct objectives.
Firstly, steady head losses are studied. The influence of the upstream and downstream conditions is shown on the head loss coefficient. When an orifice is placed close to a T-junction, the head loss coefficient changes. However, these changes do not occur for the higher orifice internal diameter.

Secondly, head losses in transient flow are evaluated when a surge tank is emptying. At the first time, the instantaneous head loss coefficient is similar to the steady value. When the head losses becomes too small for a relevant physical recordings, the head loss coefficient is decreasing until the end of the experiment. For a decreasing transient experiment, the head loss coefficient is always 5-10% smaller than the steady head loss coefficient.

This study shows different gaps in the actual knowledge about the determination of head losses. Currently, empirical relations are described in Blevins (1984) or Idelchik & Fried (1986) for a diaphragm's orifice in a long straight pipe. This specific condition is rarely satisfied in reality and physical modelling are largely used to evaluate head losses in complex flows and geometries. As these types of study are quite expensive, corrections factors should be found to take into account different types of flow fields, complex junctions and surge tanks.

6. ACKNOWLEDGMENTS

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NOTATIONS

Symbol	Effects	Units
β	Contraction ratio	[-]
d	Internal diameter of the diaphragm's orifice	[m]
D	Diameter of the connecting tunnel	[m]
g	Gravitational constant	[ms^{-2}]
H	Hydraulics head at the point i.	[m]
k	Head loss coefficient	[-]
K	Kinetic energy	[m]
p	Pressure	[Nm^{-2}]
P	Tested position in the connecting tunnel	[m]
S	Measurement section on the physical model	
v	Flow speed	[ms^{-1}]
Z	Altitude	[m]

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