HEAD LOSSES AND INFLUENCE LENGTH OF SHARP-EDGED AND ROUNDED ORIFICES UNDER STEADY FLOW CONDITIONS

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ABSTRACT

Orifices have been largely studied either for flow metering or for producing head losses. An orifice which is used as a flow meter is well defined in ISO 5167. All the geometrical parameters are defined to obtain discharges as accurate as possible. However, providing an orifice geometry which produces a certain amount of head losses could be useful as well. For example, during a refurbishment, throttling a surge tank of a high head power plant with an orifice allows the management of maximum and minimum water level followed by the management of downstream discharge control and transient events. When the discharge increase is limited, it is often efficient to place an orifice at the entrance of the existing surge tank allowing the same safety level to be kept. Actually, surge tank modifications have to be designed case-by-case. Normally, the placed orifice should produce asymmetric losses, which are defined by performing transient simulations for relevant flow directions in the whole water way system and hydropower plant.This research focuses on the evaluation of head losses and the length of the orifice influenced zone of 5 different contraction ratios (from 0.4 to 0.6) with two different orifice geometries. The influence length allows the determination as to which part of the surrounding pipe should be reinforced to avoid damages caused by cavitation.The main goal of this research is to provide the guidelines for the design of orifices in terms of head losses to the practical engineers and to avoid damages.

Keywords: Head losses; influence length; orifice; throttle; surge tank.

1 INTRODUCTION

Orifices are sudden and local variations of the pipe cross-section in a pressurized system. They can be used either as a flowmeter (Standard 2003) or to produce head losses (Gabl et al., 2011; Hachem et al., 2013). (Standard 2003) defined a standard orifice shape with a sharp angle or with rounded side as shown in Figure 1. Previous studies showed that the orifice geometry (Figure 1), e.g. the shape, the contraction ratio $\beta = d_{orifice}/d_{pipe}$ or the sharp-edged angle θ, influence significantly the produced head losses (Adam et al., 2016a; Adam et al., 2016b; Zhang and Cai 1999). Zhang and Cai (1999) evaluated the effect of different contraction shape approaches, e.g. square-edged, sharp-edged or rounded orifices, but did not evaluate the effect in both possible flow directions.

Orifices are useful to throttle surge tank in high head power plants (Figure 2). Throttling a surge tank is an efficient way to adapt existing surge tanks to follow a refurbishment, inducing an increase of the discharge flow through the waterway.

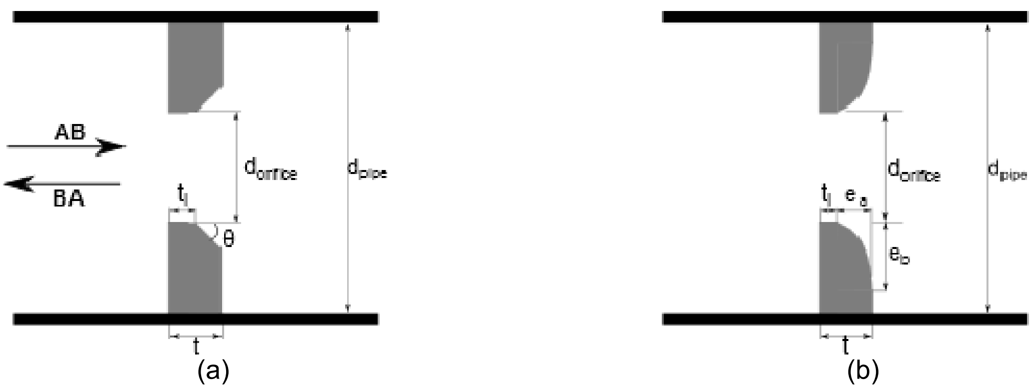


Figure 1. The two types of orifice tested in the study: (a) sharp-edged orifice and (b) rounded orifice.

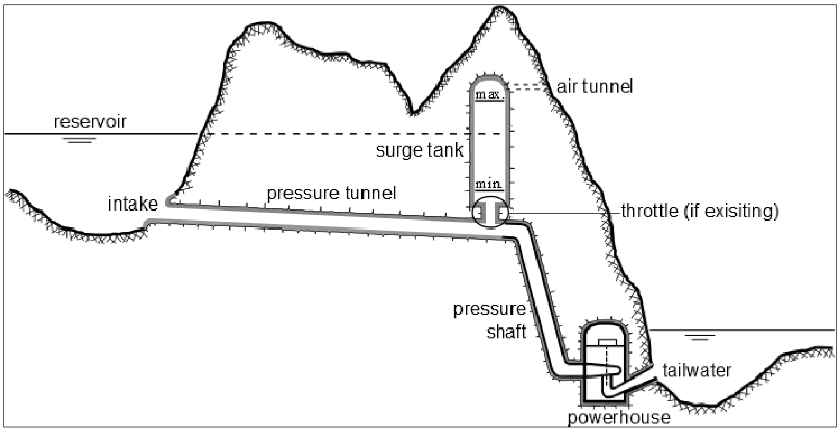


Figure 2. Schematic view of a high head power plant (courtesy of A.J. Pachoud).

2 MEANS AND MATERIALS

2.1 Physical set-up

The experimental set-up (Figure 3) was placed in the Laboratory of Hydraulic Constructions in Lausanne. It consisted of a main PVC pipe with and inner diameter D of 0.216 m and a length of 4 m. The laboratory water supply and restitution had an inner diameter of 0.150 m. Two types of flow straightener, a PVC cross and a honeycomb, were used in each direction to ensure uniform flow condition as possible in the upstream pipe section (Figure 4).

The head losses and the length influenced by the orifice could be evaluated in both flow directions (From A to B or from B to A). The pressure was recorded by piezo resistive pressure sensors, averaged on 4 points equally placed over the perimeter (top, bottom, left, right), at 12 different cross-sections for each pipe. An electromagnetic flowmeter per branch recorded the discharge for each flow direction. The pressure and the discharge were recorded during 30 s with a sampling frequency of 100 Hz.

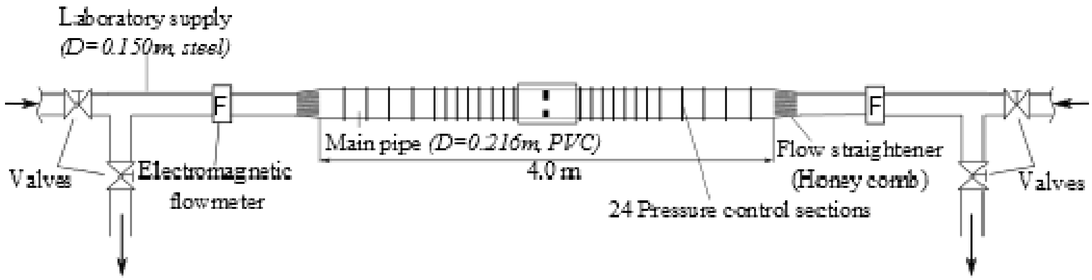
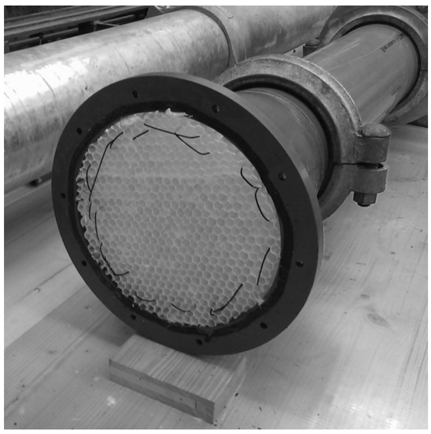


Figure 3. Experimental set-up at LCH



(a) (b)

Figure 4. Two types of flow straightener used to ensure right flow conditions at the upstream of the orifice: (a) PVC cross inside laboratory supply and (b) Honey comb in the transition pipe between the laboratory supply and the main pipe

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2.2 Tested orifices

Experimental tests were performed on two different orifice types (Figure 1) with different contraction ratio β, which is the ratio between the orifice diameter and the surrounding pipe diameter (Table 1). The orifice thickness ratio α was constant (α=0.2) and higher than thickness recommended by (Standard 2003). The shape of each rounded orifices was defined from the correspondent sharp orifices. It induced different inner thickness ratio and dimensionless semi axis for this type of orifice.

Table 1. Sharp orifices (Figure 1 (a)) with contraction ratio β ($d_{orifice}/d_{pipe}$), thickness ratio α (t/d_{pipe}), inner thickness ratio α_i (t_i/d_{pipe}) and the sharp angle θ.

	β [-]	α [-]	α_i [-]	θ [°]
S-1	0.40	0.20	0.10	45
S-2	0.45	0.20	0.10	45
S-3	0.50	0.20	0.10	45
S-4	0.54	0.20	0.10	45
S-5	0.59	0.20	0.10	45

Table 2. Rounded orifices (Figure 1 (b)) with contraction ratio β ($d_{orifice}/d_{pipe}$), thickness ratio α (t/d_{pipe}), inner thickness ratio α_i (t_i/d_{pipe}) and dimensionless semi axis β_b(e_b/ d_{pipe}).

	β [-]	α [-]	α_i [-]	β_b [-]
R-1	0.40	0.20	0.04	0.15
R-2	0.45	0.20	0.01	0.14
R-3	0.50	0.20	0.04	0.10
R-4	0.54	0.20	0.04	0.07
R-5	0.59	0.20	0.06	0.03

3 METHODS

3.1 Head losses

The head losses in the main pipe were measured for different discharges. Due to a limitation of the upstream pressure, the number of tested discharges was limited at 4 for β=0.4.The minimum Reynold number, Re, was always higher than 10^4, insuring a fully turbulent behavior of the head losses according to (Blevins 1984; Idel'cik 1969). All discharges were distributed with a constant increase of kinetic energy. The global head losses were evaluated by using all the upstream pressure sections and the pressure sections downstream of the reattachment points (Figure 5 (a)). The head losses were calculated by neglecting the friction losses, which were limited to 1 mm (the same order of magnitude of the physical error of the piezo resistive transducers) for the higher tested discharge in the downstream averaging zone. For each orifice and flow direction, the head loss coefficient relative to the main pipe cross was evaluated using the least square method as described in (Adam et al., 2016b).

3.2 Zone influenced by the orifice

For each orifices (Table 1 and 2), the length of the zone influenced by an orifice was defined such as the only variation of pressure is due to friction losses. Figure 5 (b) shows the length of the influenced zone, Lo. In this paper, L_o is measured from the upstream orifice face to the point where the first derivative of the pressure is zero. As the pressure recorded by the sensors was discrete, the first derivative was evaluated by the means of the finite difference, and more precisely the central difference (Eq.[1]). For the most upstream (resp. downstream) measured pressure, the forward (resp. backward) difference was used.

$$\frac{dp(x)}{dx} \approx \frac{p(x+\Delta x) - p(x-\Delta x)}{2\Delta x} \qquad [1]$$

If the end of the influenced zone is between two physical points, the abscissa was calculated using a linear regression between the points whose first derivative is positive and negative.

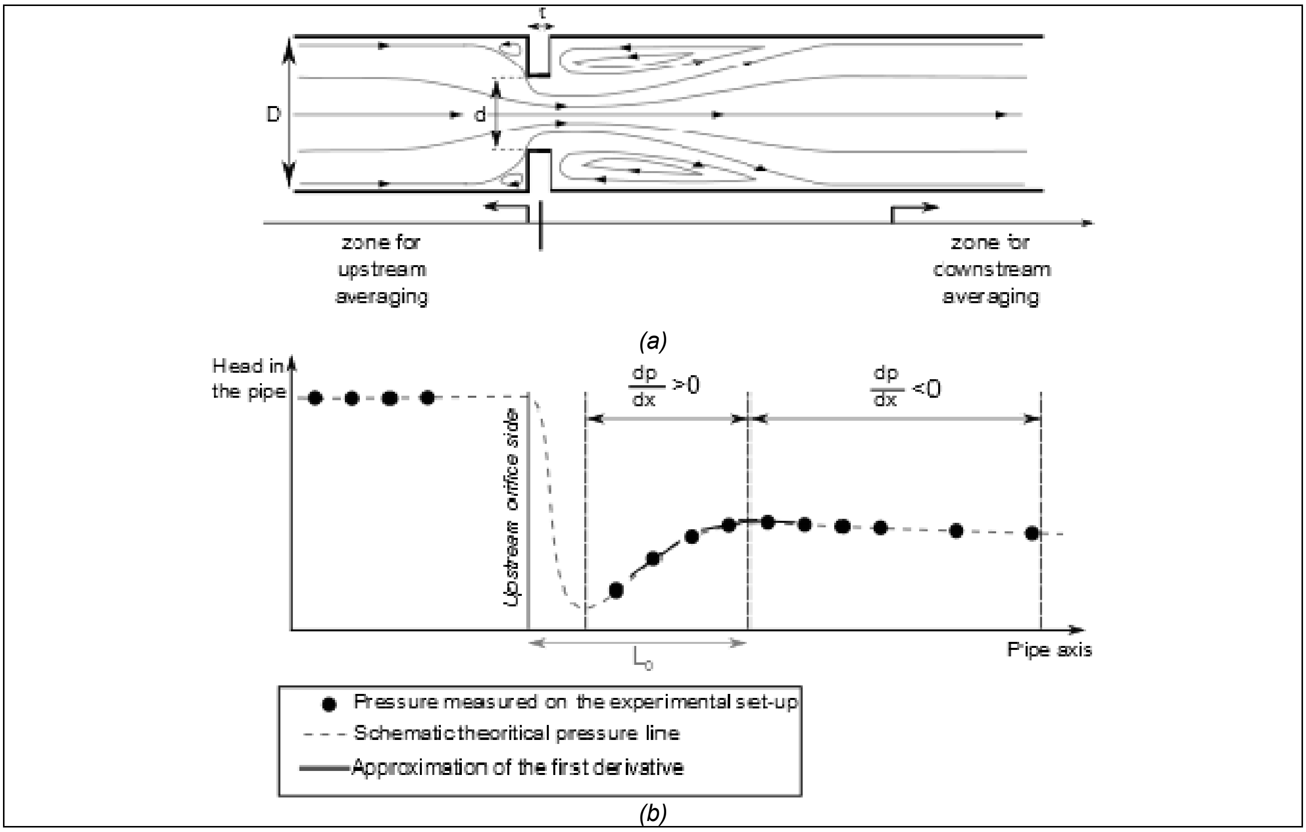

Figure 5. Schematic streamlines and pressure variation in the pipe: (a) Zones used for the averaging upstream and downstream head; (b) Definition of the zone influenced by the orifice

4 RESULTS

4.1 Head losses

Figure 5 shows the head loss coefficient for the two orifice geometries (Figure 1) in the two possible flow directions. According to Figure 6, the following observations can be made:

i. The smaller the contraction ratio β was, the higher the head loss coefficient was. Furthermore, the head losses seemed to increase with β at the inverse power 4 as described in (Blevins 1984; Idel'cik 1969).

ii. The head losses were higher in the flow direction AB than for the flow direction BA.

iii. For the flow direction BA (Figure 1), the sharp-edged orifices produced bigger head losses (around 64% higher on average) than the corresponding rounded orifices always.

iv. For the flow direction AB (Figure1), the orifice shape had little influence on the produce head losses. The flow detachment at the edge was not influenced by the downstream orifice shape. Furthermore, the results are in good agreement with an existing formula given in Eq.[2] and proposed by (Blevins 1984).

$$k_{Blevins} = \frac{\eta}{C^2}\frac{1-\beta^4}{\beta^4} \qquad [2]$$

where: η is function of β (η=0.93 for β=0.2 and η=0.38 for β=0.8) and C depends on Re (C=0.6 for Re > 10^4).

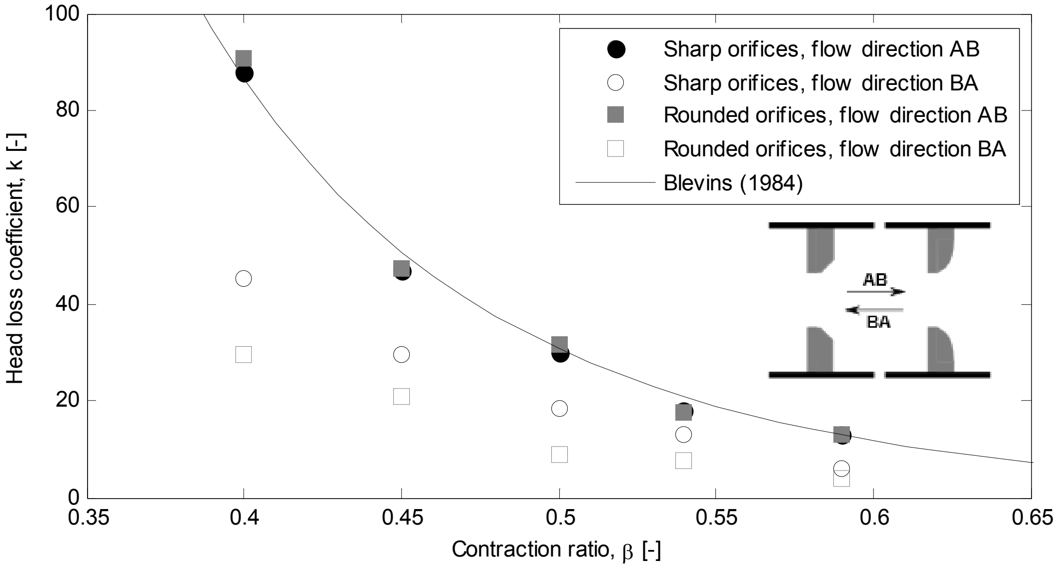

Figure 6. Head loss coefficients in both flow directions for the two types of orifice

4.2 Zone influenced by the orifice

As explained in Section 3.2, the influence length was defined so that the distance between the upstream orifice face and the point where the first derivative of the pressure line is zero. According to Figure 7 which shows the influence length lo as a function of the orifice shapes, we can made the following observations:

i. The influence length was higher for the flow direction AB than for the flow direction BA. Moreover, the influence length L_o decreased with an increase of the contraction ratio β for both geometries and flow directions. The difference between the influence lengths for each flow direction remained more or less constant (between 15 % and 20 %).

ii. For both flow direction, the difference was small between the two orifice shapes.

iii. For the flow direction AB, the influence length L_o was always higher than the recirculation length L_r defined by Jianhua et al. (2010). The difference was almost 20% for β=0.4 while it tended to decrease for higher contraction ratios (almost 10% for β=0.59).

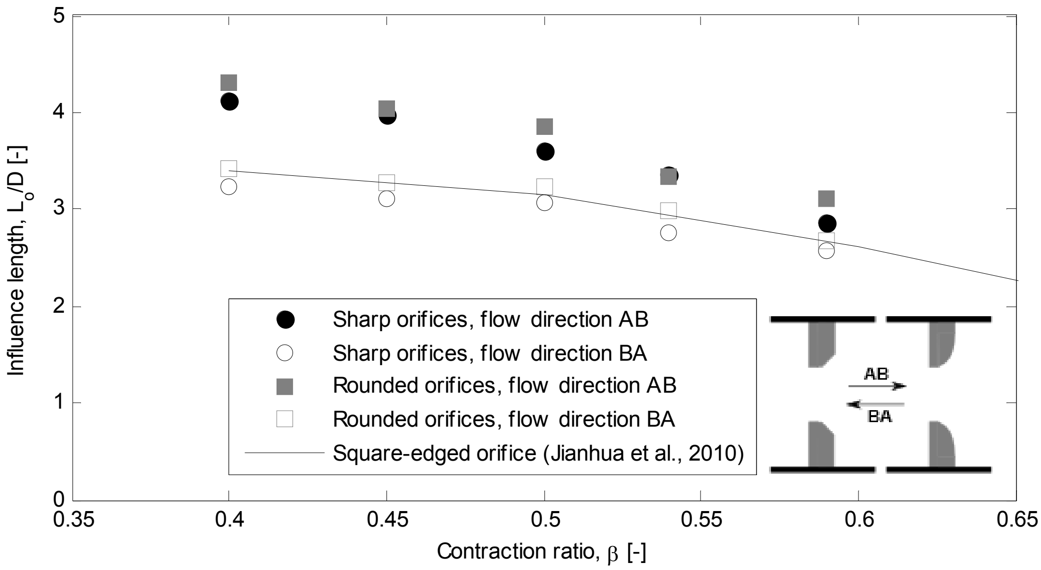

Figure 7. Length in the pipe influenced by the orifice l_o (L_o/D) for the two types of orifice

5 CONCLUSIONS

Firstly, surge tank orifices are quite efficient to adapt existing surge tanks during the refurbishment of a high head power plant. Depending on the increase of discharge and on the waterway, different orifice geometries are needed to produce an amount of head losses in and out of the surge tank. The present study focuses on the influence on the contraction ratio β and the orifice shape on the head losses and the influence zone produced by the orifice.

Secondly, two types of shape orifice were tested, i.e. sharp-edged and rounded orifices, by allowing the tests to produce the same amount of head losses in the sharp flow approach. For the contracted flow approach, the rounded orifices produced less head losses than the sharp-edged orifices. Furthermore, the head losses in the sharp flow approach (AB) agrees well with existing formula. For the gradual flow approach (BA), head losses are 40% lower for the sharp orifices and 65% lower for the rounded orifices.

Thirdly, the authors proposed a definition of the influence length produced by an orifice. The orifice shape does not affect this influence zone. However, the influence zone is higher by 15%-20% for the sharp flow approach.

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