# PRESSURE DROP AND RECOVERY ACROSS SHARP-EDGED MULTI-HOLE ORIFICES

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## Abstract

Multi-hole orifices are largely used in hydraulic pressurized systems either as flow conditioner or, placed side by side a control device, to attenuate the onset and the development of cavitation. The hydraulics of single and multi-hole orifices have been widely discussed in literature, with the main aim of identifying the most important parameters affecting their performances. In particular, it has been found by many Authors that the dissipation and cavitation characteristics of such devices are significantly affected by geometrical features, such as the contraction ratio $\boldsymbol{\beta}$, the dimensionless plate thickness $t/d_h$ and the number $n_h$ and disposition of the holes.

In order to further clarify the role played by these parameters, with particular attention for the case of multi-hole orifices, the results of two experimental campaigns, carried out by research groups of Polytechnic School of Bari and Polytechnic School of Milan in two different pilot plants, are reported and discussed. Several devices, characterized by different geometries, were tested in variable flow conditions. In particular, the equivalent diameter ratio varied between 0.2 and 0.72, the dimensionless thickness between 0.2 and 1.44 and the number of holes between 1 and 52.

The result of the two campaigns appear consistent, and confirm the remarkable dependency of the dissipation characteristics of the devices, expressed in terms of pressure loss coefficient $K$ and discharge coefficient $C_d$, upon the above mentioned geometrical parameters. A comparison to different literature models is provided. At last, the problem of estimating the pressure recovery length is also considered.

## Introduction

Multi-hole orifices are commonly used for the control and the maintenance of the efficiency of pressurized systems, being preferred to other hydraulic devices for their simple geometry and low cost. Generally, such devices are used as flow conditioners or, coupled with a control valve, used for preventing cavitation phenomena, assuring safe operating conditions (Tullis (1989)).

The hydraulics of multi-hole orifices has been widely investigated, particularly as far as the functionality of the devices as flow conditioners is concerned. Among these, Laws and Ouazzane (1995) focused their attention on their use for pre-conditioning a disturbed flow, whereas Schluter and Merzkirch (1996) and later Xiong et al. (2003) measured, by means of a PIV, the time-averaged axial velocities downstream perforated plates for defining optimal geometries. On the adoption of single- and multi-hole orifices as flow regulators, basic information have also been provided by Tullis (1989), who reported a large dataset of experimental data, both in steady and cavitating flow conditions.

A smaller number of investigations deal with the dissipating efficiency of such devices, being mainly focused on the cavitation phenomenon. The occurrence and influence of cavitation development in perforated plates was experimentally investigated by Fratino (2000), who found results similar to those collected by Govindarajan (1972) and Tullis and Govindarajan (1973). More recently, Malavasi et al. (2008, 2010) carried out experimental activities in order to describe the flow behavior of perforated plates in cavitation conditions.

The dissipating efficiency of perforated plates, in absence of cavitation phenomena, was investigated by Gan and Riffat (1997) and Erdal (1997) who, through the comparison between CFD and experimental data, detected the dependency of the induced pressure drop on the number and disposition of the holes and on the plate thickness. Fratino (2000) carried out an experimental and numerical study of the flow through multi-hole plates, providing also an analytical formula for improving the estimate of the pressure drop. The Author proposed other results on different geometries (Fratino and Pagano (2011)) confirming the former outcomes.

A review of literature data in case of single- and multi- hole plates is reported in ESDU (1981) and ESDU (2007), where a detailed investigation of the key factors for computing energy losses as far as some available empirical models are introduced. Malavasi et al. (2008, 2010) carried out a large experimental campaign in order to describe the flow behavior of single and multi-hole orifices in cavitation

conditions. Tests were mainly oriented to determine the influence of the most significant geometrical parameters and flow parameters on the dissipation rate. Zhao et al. (2011) studied the dissipation characteristics of several multi-hole orifices of 2 mm thickness, and reported a simple formula to evaluate the pressure drop.
The dissipation characteristics of multi-hole orifices are usually quantified by means of the dimensionless pressure loss coefficient $K$, defined as:

$$K = \frac{\Delta P}{0.5 \rho V^2} \tag{1}$$

in which $\Delta P$ is the net pressure drop across the device, $\rho$ is the fluid density and $V$ is the pipe bulk-mean velocity. Otherwise, reference can be made to the discharge coefficient $C_d$, defined as the ratio between the actual flow rate through the orifice and the theoretical volume flow rate, as computed according to Bernoulli equation, and ranging between 0 and 1 (Govindarajan (1972), Tullis and Govindarajan (1973), and Ball et al. (1975)). $C_d$ can be evaluated and related to $K$ as below:

$$C_d = \frac{v}{\sqrt{\frac{2 \cdot \Delta P}{\rho} + v^2}} = \frac{1}{\sqrt{K+1}} \tag{2}$$

Under no cavitating conditions, both $K$ and $C_d$ are mainly influenced by the geometry of the device, defined, for a square-edged plate with holes of uniform size, by the following groups: 1) the equivalent diameter ratio $\beta$, which represents the square root of the total open area ratio; 2) the dimensionless thickness $t/d_h$, i.e. the ratio between the plate thickness $t$ and the hole diameter $d_h$; 3) the number of holes $n_h$; 4) the distribution of the holes across the screen. The losses are also influenced by the friction factor of the holes $\lambda$ but such dependence was found negligible for the plates considered in the present work. At last, an important role is played by the Reynolds number but, as observed by many Authors (Fratino (2000), Malavasi et al. (2008, 2010), Zhao et al. (2011)) a range of self-similarity with respect to this parameter can be detected. In the present work, we will refer to $K$ and $C_d$ as the mean values in the self-similarity region.
Some models for the evaluation of the pressure loss coefficient $K$ through a multi-hole orifice are available in literature. These models generally start from the case of single-hole orifice, where, upstream the device, the flow separates and forms a jet which goes on contracting until it reaches a minimum section in the *vena contracta* plane, and then expands to the pipe wall again. The way in which the jet expands is dependent upon the dimensionless thickness $t/d_h$. For taking all these features into account, Miller (1990) and Idelchik (1986) developed semi-empirical models. Those formulas are said to be applicable to the multi-hole orifice case, therefore assuming that the effect of number and disposition of the holes is negligible. In particular, Miller proposed the following formula:

$$K = \frac{C_0 \cdot \left(1 - \alpha\beta^2\right)^2}{\alpha^2 \beta^4} \tag{3}$$

in which $C_0$ is a coefficient depending upon $t/d_h$, while $\alpha$ is the jet contraction coefficient. As reported in Fratino (2000), $C_0$ can be calculated by the following empirical expression, assumed valid for $0.1< t/d_h<3.0$:

$$C_0 = 0.5 + \frac{0.178}{4 \cdot \left(t/d_h\right)^2 + 0.355} \tag{4}$$

On the other hand, Idelchik introduced the following equation, valid for $t/d_h>0.015$:

$$K = \frac{0.5\left(1-\beta^2\right)^{0.75} + \tau\left(1-\beta^2\right)^{1.375} + \left(1-\beta^2\right)^2 + \lambda \cdot \frac{t}{d_h}}{\beta^4} \tag{5}$$

in which $\tau$ is a coefficient depending on $t/d_h$.
Finally, it is worth to mention the role of the pressure recovery length $L_r$ in defining the performances of perforated plates. Despite the lack of consistent literature studies, a reliable estimate of $L_r$ appears crucial for the design, as a better behavior is associated to plates requiring lower downstream lengths to complete the partial pressure recovery, and thus inducing reduced flow disturbances.
In the present paper, the results of experimental campaigns performed in two different pilot plants are reported and discussed. The dependence of the dissipation characteristics of multi-hole orifices upon the most significant geometrical parameters in the range of self-similarity with respect to the Reynolds number is investigated. A comparison to the literature formulas reported above is reported.

## Experimental setup

Tests were carried out by two research groups of Polytechnic School of Bari and Polytechnic School of Milan.
Experiments of the former group have been performed in the Laboratory of the Department of Water Engineering and Chemistry at Polytechnic of Bari. The plant is made of ∅ 100 and ∅ 200 mm steel pipes, supplied by a pump able to guarantee pressures of about 9.0 bar and flow rates up to 100 l/s. The pressure taps are located 1$D$ upstream and 10$D$ ($D$ being the pipe diameter) downstream the device location, with other measurement points (0.5, 1, 2, 3, 4, 5, 7 $D$ downstream) used for defining the pressure recovery

length. Tests were performed referring to different downstream pressure values, to make the results independent from possible uncertainties due to the pressure scale effects.

The experimental tests were performed by the research group of Polytechnic School of Milan in a pilot plant located at Pibiviesse S.r.l, Nerviano, Italy. The rig consists of 10ò and 12ò steel pipes, supplied by a pump able to guarantee pressures up to 10 bar. The diameter of the testing section is 3ò. The pressures were measured by means of pressure transducers located 2*D* upstream and 6*D* downstream the device, and in other intermediate locations (1*D* upstream and 1, 2, 3, 4, 5, 7 *D* downstream).

Table 1 summarizes the geometrical characteristics of the plates used in this work, which differ in: diameter of the holes; number and distribution of the holes; dimensionless thickness. A single-hole orifice was also tested.

Table 1: Main geometrical features of the tested plates.

| | | |
|---|---|---|
| Number of holes | $N_h$ | From 1 to 52 |
| Dimensionless thickness | $t/d_h$ | From 0.2 to 1.44 |
| Diameter ratio | $\beta$ | From 0.2 to 0.72 |

## Main results

### Energy Dissipation

In the present section, the dependence of the dissipation characteristics of multi-hole orifices ï expressed in terms of both pressure loss coefficient *K* (Eq. (1)) and discharge coefficient $C_d$ (Eq. (2)) ï upon the most significant geometrical parameters is analyzed, also referring to the main literature outcomes.

The gross behaviour of the data is first studied with reference to the discharge coefficient $C_d$, as its narrow variability range allows a complete overview of the results. The choice of considering $C_d$ instead of *K* allows also lowering the effect of the parameters other than the $\beta$.

Figure 1 reports the trend of $C_d$ as a function of $\beta$ for our experimental results together with data collected from technical literature about the single-hole orifice case (Tullis and Govindarajan (1973), Zhang and Cai (1999), Ball (1975)).

The literature formulas described above are also reported; since the models of Miller (Eq. (3)) and Idelchik (Eq. (5)) take the dependence upon $t/d_h$ into account, for clarity in Fig. 1 are drawn the curves with $t/d_h$=0.5 only. The results confirm that the equivalent diameter ratio $\beta$ is the dominant geometric characteristic affecting the losses (Malavasi et al. (2010), Zhao et al. (2011)), even if a significant dispersion can be detected, especially for low values of $\beta$. The dispersion of the data could be related primarily to $t/d_h$, and, for our data about multi-hole orifices, to $n_h$ and the distribution of the holes.

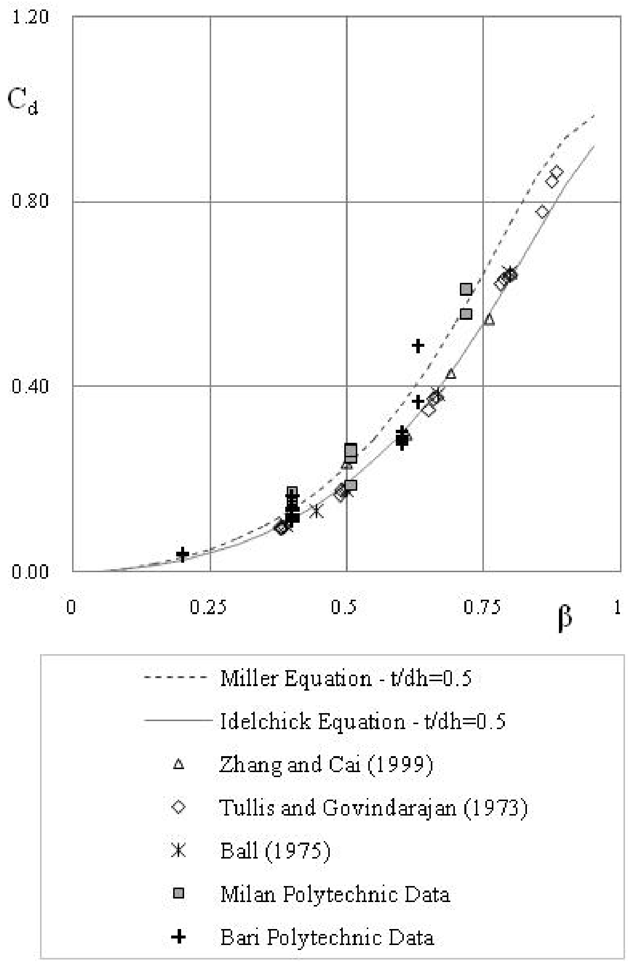



Figure 1: Trend of the discharge coefficient $C_d$ as a function of the equivalent diameter ratio $\beta$.

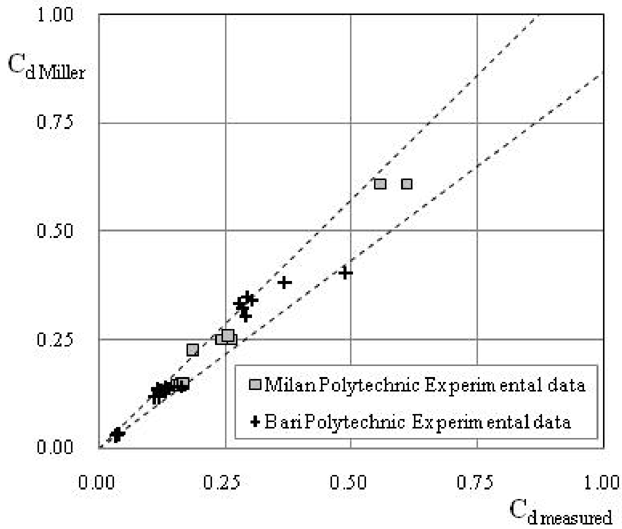
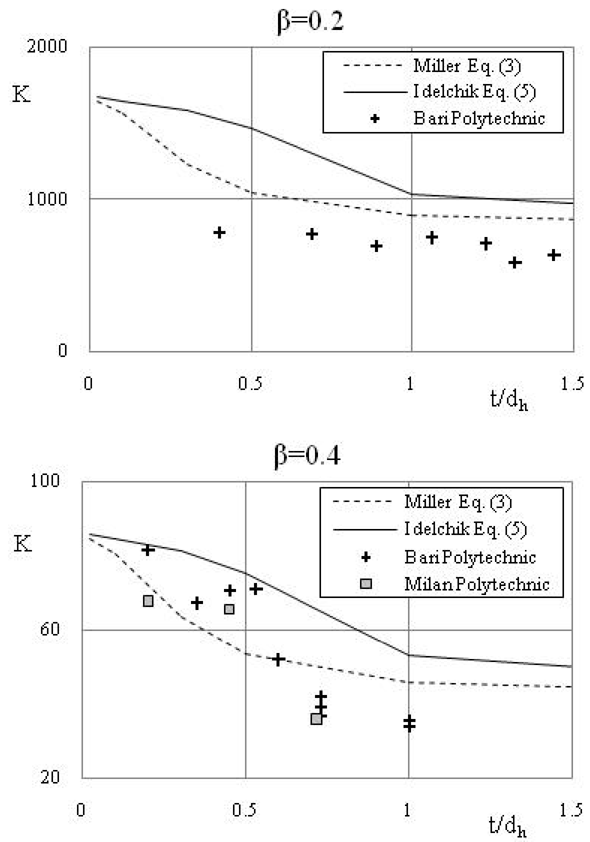



Figure 2: Comparison between the experimental values of the discharge coefficient $C_d$ and the corresponding estimated values according to Miller equation.

At first sight, when plotted in a graph like that of Figure 1, the literature curves of Miller and Idelchik, even if referred to the arbitrary case of $t/d_h$=0.5, appear able to catch the gross dependence of $C_d$ upon $\beta$ both for single and multi-hole orifices. However, a more detailed analysis reveals that the deviation between calculated and experimental data can be significant, reaching up to about 20% in terms of $C_d$ (Figure 2), corresponding to about 44% in terms of $K$.

A comparison between the experimental data and the above mentioned literature models in terms of pressure loss coefficient $K$ is reported in Fig. 3, which depicts, for different values of the equivalent diameter ratio $\beta$, the pressure loss coefficient $K$ versus the dimensionless thickness of $t/d_h$. Only the qualitative trend of $K$ as a function of $t/d_h$ is caught by the curves of Miller (Eq. (3)), and Idelchik (Eq. (5)). The dispersion of the data, especially for low values of $\beta$ and $t/d_h$, indicates that the number and the disposition of the holes have some influence on the pressure losses, therefore reducing the validity of all the existing literature formulas which, as highlighted above, neglect the effect of these parameters.

On the basis of our data only, itôs not possible to highlight the effect of $n_h$ upon the dissipation characteristics of multi-hole plates. However, an overall look to the data seems to indicate that the pressure loss coefficient $K$ tend to decrease when the number of holes increases, $\beta$ and $t/d_h$ being the same, confirming the conclusions of other Authors (Erdal (1997).



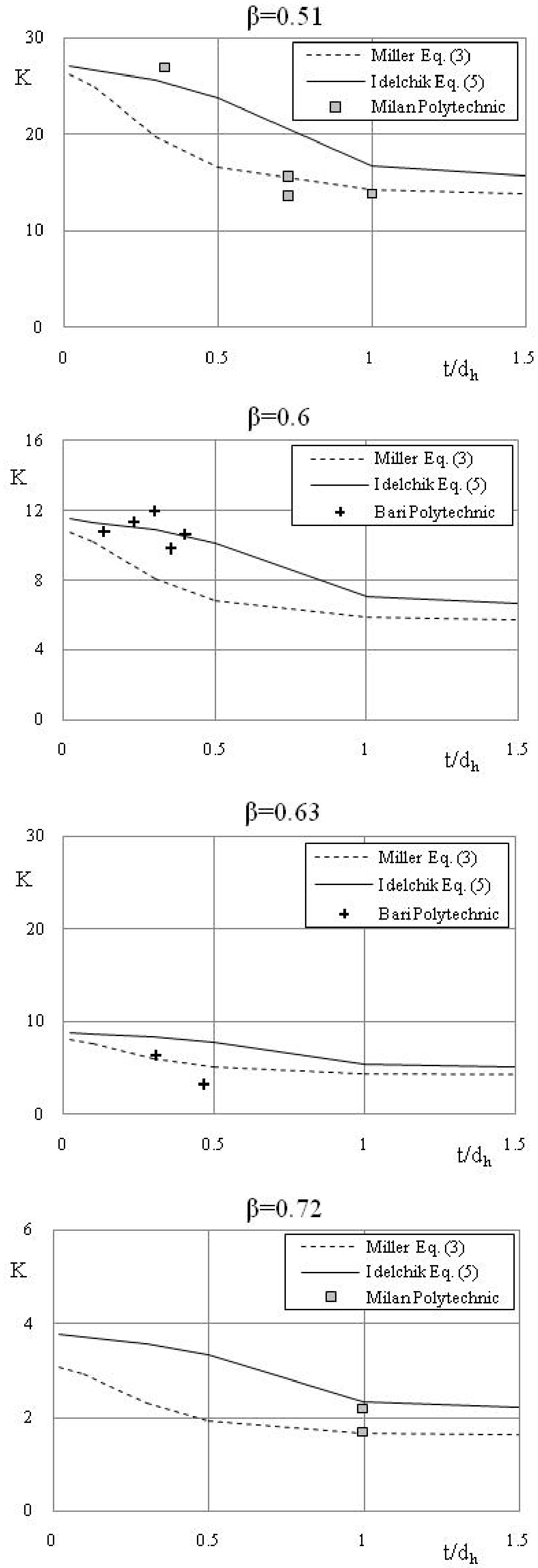
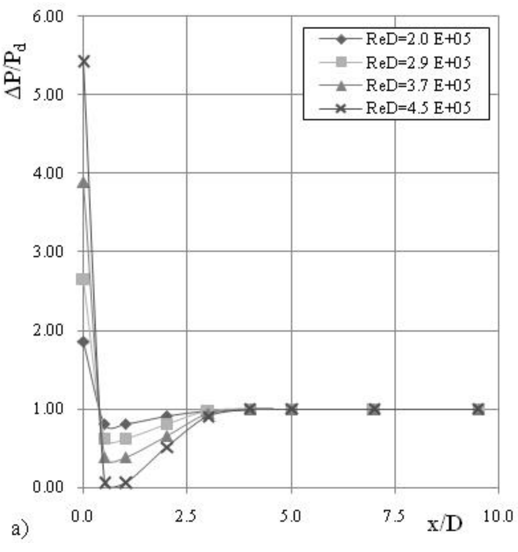




Figure 3: Trend of the pressure loss coefficient $K$ as a function of the dimensionless thickness $t/d_h$ for plates having fixed values of the diameter ratio $\beta$.

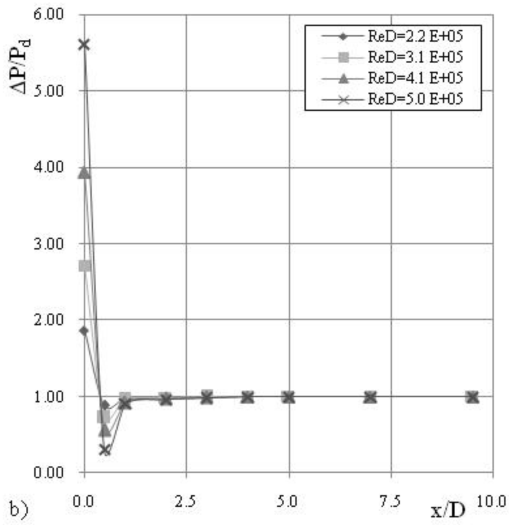
**Pressure recovery length**

During the design phase, the knowledge of the pressure recovery profile is crucial for correctly estimating the length for a complete reattachment of the flowing jet, above all when particular configurations, like multi-hole orifices located in series, have to be adopted. Figure 4 shows the ratio between the section-by-section pressure drop $\Delta P$ and the downstream pressure value $P_D$ versus the dimensionless distance from the step $x/D$ for a single and a 5-holes plate. For both devices, the equivalent diameter ratio is 0.4 and the testing pressure is 0.5 bar, while the relative thickness $t/d_h$ is 0.2 and 0.45 for the single and the multi-hole plate respectively. Figure 4 depicts the curves corresponding to different values of the pipe Reynolds number $Re_D=V_pD/\nu$, where $V_p$ is the pipe bulk-mean velocity and $\nu$ the kinematic viscosity of the fluid. The experimental results first indicate that, both for single and multi-hole orifices, the pressure recovery length is not dependent upon the $Re_D$.

Few information on the role of the holes number $n_h$ can be deduced. As reported by Tullis (1989), a multi-hole orifice requires a shorter length for a complete pressure recovery with respect to a single-hole orifice, probably because of the specific distribution of the free area. Despite at first sight out data seem to confirm such behaviour, a comparison between the two plots of Fig. 4 could be strictly made only if we were able to consider negligible the influence of $t/d_h$ on the pressure recovery length. However, such hypothesis cannot be strictly made even with respect to the pressure drop coefficient $K$: in fact, as it can be inferred from Fig. 3, the model of Miller (Eq. 3), unlike that of Idelchik (Eq. 5), indicates a remarkable influence of $t/d_h$ on $K$ in the range considered ($\beta$=0.4, $t/d_h$ from 0.2 to 0.45). More detailed analyses are therefore required to further clarify the actual influence of holes number and disposition on pressure recovery length.




a)




b)

Figure 4: Trend of the non-dimensional pressure recovery profile downstream of a single-hole plate (a) and a 5-holes plate (b) both having $\beta$=0.4 and tested for a fixed downstream pressure of 0.5 bar and for increasing values of the pipe Reynolds number $Re_D$.

At last, it is worth noting that although pressure measurements have been performed in different locations in the two campaigns (-1$D$/10$D$ and -2$D$/6$D$ for the research groups of Bari and Milan respectively), no significant discrepancies are expected on the results. As it can be inferred from Fig. 4, the difference in the downstream pressure tap locations is negligible, since at a distance of 6$D$ downstream the step the pressure recovery is completed and the distributed friction losses between 6$D$ and 10$D$ (therefore those between -2$D$ and -1$D$) are without any significance over such a small pipe length.

## Conclusions

In this work the dissipation characteristics of sharp-edged multi-hole orifices under no cavitating conditions has been investigated. Experimental data were collected in two experimental campaigns by two research groups of Polytechnic School of Bari and Polytechnic School of Milan in different pilot plants.

Firstly it has been confirmed that the equivalent diameter ratio $\beta$ is the main parameter affecting the losses, as both the pressure loss coefficient and the discharge coefficient are dependent upon $\beta$ (Figure 1). However, both the dimensionless thickness and the number and disposition of the holes have some influence on the pressure losses (Figures 1, 3). The literature formulas of Miller (equation (2)) and Idelchik (equation (3)), derived for the single-hole orifice case, can only catch the gross dependence of the discharge coefficient upon the diameter ratio (Figure 1), but are inadequate to describe all the characteristics of the phenomenon.

For a given orifice (either single- or multi-hole), the pressure recovery length is independent on the Reynolds number. The role of the number of holes $n_h$ is still uncertain. At first sight, lower distances seem to be required for completing the pressure recovery in case of multi-hole orifices rather than of single-hole orifices, for a fixed contraction ratio $\beta$. However, more detailed analyses are required to confirm such behaviour.

Nevertheless, the experimental campaign demonstrated as additional experimental tests on multi-hole plates are necessary for correctly defining, also quantitatively, the role of geometrical parameters mostly influencing the dissipating efficiency of a wide range of geometrical configurations.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